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eDIM: further development of the method to assess the ease of disassembly and reassembly of products

Application to notebook computers

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Abbreviations

eDIM	ease of disassembly method/metric
EoL	end of life
HDD	hard disk drive
ICT	information and communication technology
IDC	International Data Corporation
JRC	Joint Research Centre
LCD	liquid-crystal display
RAM	Random-access memory
SSD	solid state drive
TMU	time measurement unit
WEEE	waste electrical and electronic equipment

Definitions

Product is any goods or service with a specific functionality and composed by a set of linked discrete components (Lambert and Gupta, 2005).

Sub-assembly is a connected set of components which can be separated as a whole.

Component[1] is a constituent part of a product which cannot be physically divided into smaller parts without losing its particular function.

Three types of components can be distinguished (Lambert and Gupta, 2005):

- homogeneous components are made of homogeneous materials; mixtures and alloys are also considered to be homogeneous materials;
- composite components are made from different materials fastened in an irreversible fashion, for instance in a sandwich structure;
- complex components are a group of homogeneous components linked irreversibly, for instance printed circuit boards.

Connection is a physical link between components.

Connector[2] is a device providing connection and disconnection to a suitable mating component (International Electrotechnical Vocabulary).

Assembly consists of bringing components together and fitting them into a specified configuration (BS 8887-2:2009).

Disassembly[3] is a process whereby an item is taken apart in such a way that it could subsequently be reassembled and made operational (IEC/PAS 62596:2009).

Complete disassembly is a process whereby a product is separated into all its components.

Partial or incomplete disassembly is a process in which the separation of components only reaches a certain level (depth) of disassembly. With incomplete disassembly, not all of the components are separated, but rather only certain targeted components are separated in accordance with particular criteria. This is also called selective disassembly.

Manual disassembly is a disassembly method based on manual operations which can be assisted by (possibly electrical or pneumatic) hand tools (Vanegas et al., 2014).

Disassembly task is the basic disassembly action; therefore it cannot be further disaggregated. Disassembly tasks can be classified as preparatory tasks (e.g. changing tools, positioning the product) or actual tasks (e.g. unscrewing fasteners) (Lambert, 2006; Scharke and Scholz-Reiter, 2003).

Disassembly sequence is the successive order in which the disassembly tasks are carried out.

Disassembly depth is the extent to which the disassembly process is performed. The optimal disassembly depth can be determined by economic analysis, to evaluate the trade-off between revenues and costs (Langella et al., 2007).

Reassembly is the process of assembling a product, after its complete or partial disassembly, to bring it to its original configuration (built upon other definitions from BS 8887-2:2009).

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[1] As the part that cannot be further disassembled, it keeps its intrinsic properties intact when separated from a product (Lambert and Gupta, 2005).

[2] Connectors (and/or fasteners) are specialised components or parts of a component(s) used to mechanically or chemically connect different components with or without a certain degree of freedom of motion.

[3] Thus, disassembly consists of the non-destructive taking apart of an assembled product into constituent materials and/or components (BS 8887-2:2009).

Complete reassembly is a process whereby all components of a disassembled product are brought together into its initial configuration.

Reassembly sequence is the successive order in which the reassembly tasks are carried out.

Ease of disassembly is the ease with which the product (or component) can be disassembled, which is assessed through the method proposed in this report.

Ease of reassembly is the ease with which the product (or component) can be reassembled after being disassembled, which is assessed through the method proposed in this report.

Ease of disassembly metric (eDIM) is calculated on the disassembly sequence and on the reassembly sequence. eDIM consists of the sum of two metrics:

- $eDIM_D$: ease of disassembly metric calculated on the disassembly sequence ('ease of disassembly metric');
- $eDIM_R$: ease of disassembly metric calculated on the reassembly sequence ('ease of reassembly metric').

Acknowledgements

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The authors would like to thank De kringwinkel Hageland located in Tienen, Belgium and Arrow Value Recovery located in Mechelen, Belgium, for all the information and suggestions provided, which were essential for the development of this study.

Executive summary

The method to assess the 'ease of disassembly' of products (eDIM) was developed in prior research and published as a JRC technical report in 2016 (Vanegas et al., 2016) and as a scientific paper in 2017 (Vanegas et al., 2017). eDIM was developed to evaluate the ability or ease with which components can be disassembled from products to facilitate repair, remanufacture and/or reuse. In a previous JRC technical report, a database of disassembly tasks was built based on the Maynard operation sequence technique (MOST) (Zandin, 2003), which provides values for elementary manual movements. The method was then tested on an LCD display case study. Results showed how the information about the disassembly sequence of a product (including types of fasteners and tools required) can be used on a spreadsheet to assess partial or complete disassembly, through the proposed ease of disassembly metric.

The present study further develops the eDIM method and database, in particular based on feedback received from stakeholders on the previous technical report. The study also aims to demonstrate the applicability of the method on some sample notebook computers. Similarly to the first report, this study aims to provide scientific evidences for regarding the ease of disassembly, reparability and reusability, and to serve as basis for the potential development of standardised metrics.

First of all, the report includes a review of available statistics about frequent failures of notebook computers. The most common notebook components reporting damages or breakages are, for example, batteries, keyboards, LCD screens and memory storage drives. Moreover, two Belgian facilities that reuse, repair and refurbish notebooks were visited and interviewed by the authors to obtain better insight into how enhanced component fastening could facilitate their processes. Furthermore, the study was complemented by laboratory experiments on the disassembly of some of the main components of a notebook, such as batteries, hard disk drive (HDD) or solid state drive (SSD), CD/DVD player, motherboard and LCD screen. The experiment was run on 39 sample notebooks produced between 2004 and 2011.

Based on the literature review, the plant visits and the performed experiments, the eDIM method was further developed and the associated database was extended to improve its applicability to a wider range of products. In particular, this further development aimed to address the following key points:

- the need to enlarge the eDIM database, with other types of connectors, such as cable connectors, cable plugs and glues requiring wedge/pry and peel actions to be released;
- the need to further develop the eDIM to include reassembly operations;
- the need to test the eDIM method for partial disassembly and partial reassembly;
- the need to test the method on a broader range of products including small, portable electronics.

The updated eDIM method allows now to evaluate both the ease of disassembly ($eDIM_D$) and the ease of reassembly ($eDIM_R$) metrics. The sum of the two metrics ($eDIM_D$ and $eDIM_R$) allows the estimation of the overall effort needed for disassembling and reassembling one or more components.

The updated eDIM method was then tested on an 11″ notebook manufactured in 2011, referred to as notebook 1, and a 13.3″ notebook from 2015, referred to as notebook 2. Notebook 1 was selected as a case study because of its compact design, production in large quantities and online availability of detailed disassembly and repair instructions (4). For notebook 1 the eDIM method was applied based on data retrieved from empirical experiments, as well as data for disassembly and repair obtained from the online disassembly instructions. Notebook 2 was selected as a case study because disassembly

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(4) Ifixit.com website.

guidelines have been published by the manufacturer and it obtained a relatively high reparability assessment from a specialised company (^{5}). For notebook 2 the eDIM method was applied based on data and disassembly guidelines provided by manufacturer and by online websites.

The objective of the report was to determine the applicability of the eDIM method to different case-studies. The report did not aim to assess the design of the studied products. Given the disassembly sequences of the two notebooks, for complete or partial disassembly to reach target components, the application of the method was possible for both cases, assuming that the database of disassembly operations was sufficiently wide to cover all the tasks involved in the disassembly and reassembly of the products. The application of the eDIM method to the two case studies also provided interesting insights in terms of design for disassembly. Even though the eDIM for notebook 1 and for notebook 2 were quite different (the eDIM for notebook 2 was 69 % higher (^{6}) than the eDIM for notebook 1), in both cases $eDIM_D$ contributed to about 43 % of the total eDIM, while $eDIM_R$ contributed the remaining part. In addition, the eDIM related to the partial disassembly to reach the battery was quite similar (eDIM for notebook 2 was 16 s smaller than eDIM for notebook 1), while the partial disassembly to reach the motherboard provided a more significant difference (eDIM for notebook 2 was 37 s smaller than eDIM for notebook 1).

Finally, the method was developed further to integrate additional optional factors (i.e. factors not necessarily required for a standardised method but that could increase the precision of the disassembly assessment in certain conditions), such as the labelling of different connectors and the need for special tools. These factors can be used by designers and manufacturers for design purposes, but were not conceived for standardisation needs, as they may be affected by the subjectivity of the user. When these factors were studied, it was possible to see an additional difference in the eDIM of the two computers, particularly notebook 1.

The present study shows that eDIM can be applied in a robust manner to assess the ease of disassembly and reassembly for the purposes of reuse, repair and remanufacturing, for a wide range of notebook computers, and in a verifiable manner. Moreover, it was demonstrated that the eDIM database is flexible and that it can be expanded with additional types of operations (reference values are always based on MOST values for elementary manual movements, reducing the subjectivity of the assessment), to include new sequences that could be relevant for the disassembly and reassembly of new products in future.

Calculating the ease of disassembly and the ease of reassembly metrics for a given case study is a relatively easy task, once the disassembly/reassembly sequence is available. Users of the eDIM (e.g. designers, manufacturers, repairers and reuse operators) can implement the input sequence in the provided eDIM spreadsheet choosing the predefined list of operations. The spreadsheet, then, provides the result of the eDIM according to the operations defined. Third-party verifiers can easily check the correctness of the eDIM calculation, in a short time and with limited effort, based on the documentation provided.

The outcomes of the study also show that the eDIM method is characterised in all its parts (especially the database population) by low subjectivity, which allows this approach to be used as a basis for standardised methods.

(^{5}) This product receive a score of 7 out of 10 (10 is easiest to repair) from iFixit rating.

(^{6}) The higher the eDIM index is, the more difficult it is for the product (or component) to be disassembled.

1. Introduction

Resource efficiency has become a prominent goal in several EU policy instruments, as outlined in the *Roadmap to a resource-efficient Europe* (European Commission, 2011). Increasing resource efficiency is key in improving productivity, driving down costs and boosting competitiveness in Europe. The 'Raw material' initiative (European Commission, 2008) identifies end-of-life (EoL) products as being an important source of secondary raw materials for the EU. In Europe, waste of electrical and electronic equipment (WEEE) is collected and treated according to the EU WEEE directive (European Union, 2012) with clear objectives in terms of mass recovery and recycling. In addition, Article 4 of the WEEE directive encourages product designs to facilitate reuse, dismantling/disassembly and recovery of components and materials. The reuse of products and components offers relevant opportunities to improve the productivity of raw materials, in particular that of critical raw materials (Mathieux et al., 2017). Furthermore, European policies could promote measures for the ease of disassembly to improve the reuse and repair of products. These measures could also be synergetic with similar measures for other policy contexts, such as waste policies (to facilitate the design for recycling) and eco-labelling initiatives (to promote best practices and reward pro-active manufacturers).

However, to date, reuse, disassembly and repair aspects of products have not been widely addressed by policy instruments. One of the main reasons for this gap is the absence of standards to measure and verify product performances related to material efficiency, including reuse and disassembly efficiency (Tecchio et al., 2017). Some standardisation activities on this field have been initiated by the European Commission and are currently on-going (European Commission, 2015).

The method to assess the ease of disassembly of products (eDIM), developed in prior research (Vanegas et al., 2016), can serve as background information and as an example for these standardisation activities. The eDIM method evaluates the ability or easiness with which components or assemblies can be removed from products to facilitate repair, remanufacture, reuse or to enhance recycling.

The goals of this study are:

- to further develop the eDIM method based on a new application to some sample notebook computers, a product group currently under review for the Ecodesign directive;
- to discuss the applicability of eDIM as a standardised method for the assessment of the disassembly and the reassembly of certain components from products, for the purposes of repair, remanufacture and reuse.

In addition, the method has also been further developed to address comments received from different stakeholders on the technical report outlining the eDIM method and comments received during the presentation of the method at the CEN/Cenelec Joint Technical Committee, in January 2017. The methodological aspects, which will be addressed in the presented study, relate to the following main topics:

- applicability of the eDIM method to a broader range of products including small, portable electronics;
- extension of the eDIM method to include a wider range of connectors, such as glues requiring wedge/pry and peel actions to be released;
- applicability of the eDIM method for complete and partial disassembly, as well as for complete and partial reassembly.

The present report begins with an analysis of the information collected to further develop the eDIM method and database (section 2). The relevant information was retrieved through available literature and statistics, direct interviews with stakeholders and experiments performed by the authors on some sample notebook computers.

Based on this analysis, the eDIM database was further developed and this activity is presented in section 3. The eDIM approach was then tested on two notebook computers, introduced in section 4, with results available in section 5.

The discussion on results and considerations for the implementation of the eDIM method, as well as for future research, are reported in section 6. Final remarks conclude the report with the key points addressed in section 7.

1.1. Summary of the eDIM method, as in Vanegas et al. (2016)

The eDIM method is explained in detail in the JRC technical report *Study for a method to assess the ease of disassembly of electrical and electronic equipment* (Vanegas et al., 2016) and on the paper recently published on the journal *Resources, Conservation and Recycling* (Vanegas et al., 2017). The reader is encouraged to refer to these documents for further details on the method, while a summary of the required steps to estimate the ease of disassembly through eDIM is provided below.

1. In the first step, the disassembly sequence to either partially or completely disassemble the product is set as a pre-requisite of the calculation (7). This sequence lists the components in the order considered best to either reach the targeted component(s) or to completely disassemble the product.
2. In the second step, the sequence of connectors that should be released to extract each component is listed. The type of fastener can be selected from the developed database and the number of identical connectors that need to be released to release the component must be provided.
3. In the third step, the tool required to release every connection is selected from the database. If applicable, the user can also select that the connection be released by hand.
4. Finally, the number of product manipulations required to get (better) access to the connections or components to be released is determined. If after manipulation the visible surface of the connection is less than 5mm² and, accordingly, it is more difficult to identify connectors during the disassembly process, the user also marks a checkbox to indicate this.
5. Based on the input provided and information from the database that was set up for the eDIM method, the ease of disassembly of the product is calculated. The calculation takes into account the effort required for the different disassembly categories: tool change, identifying connector, positioning a tool relative to the connector, disconnecting different types of connectors and removing the released component. It should be stressed that the output is an estimation of the average required disassembly effort based on the provided sequence, which is defined by the user. Accordingly, it is up to the user to define the most efficient disassembly sequence, which would also be the disassembly sequence that an experienced operator would follow.
6. Based on the total calculated eDIM to access a specific component and/or to disassemble the complete product, the user can verify whether internal and/or external targets have been achieved.
7. Based on the calculated eDIM per component, divided into the different categories (i.e. tool change, identifying, positioning, disconnection and removing), the user can identify opportunities to improve the ease of disassembly of the analysed product.

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(7) For example, the sequence is provided by product's designers and manufacturers or by experts who know the architecture of the product.

2. Technical background

This chapter aims to summarise the technical and scientific background needed to enlarge the eDIM database and to evaluate the ease of disassembly metric of notebook computers.

There are several reasons to disassemble (and reassemble) a product. For electric and electronic devices, disassembly is mainly done for repair or upgrade purposes. While for the latter option no statistics were found in literature, section 2.1 provides detail about the components most often damaged in notebooks, which often require disassembly for repair services or replacement. A more detailed analysis of the literature available for the whole personal-computer product group is available in the JRC technical report *Analysis of material efficiency aspects of personal computers product group* (Tecchio et al., 2018). Section 2.2 describes the interviews and the plant visits of the authors to two companies that reuse, repair and refurbish, among other electronic products, notebook computers in Belgium, to obtain better insight into the processes used to disassemble and reassemble the products. Finally, section 2.3 is devoted to the experiments conducted by the authors on some sample notebook computers, in order to evaluate the ease of disassembly of key components such as batteries, motherboards, LCD modules and memory storage drives.

2.1. Literature on frequent failures

A recent International Data Corporation (IDC) study among 800 United States organisations showed that the average annual failure rate of notebooks is 18 % (average of a company's notebooks requiring repairs of any kind, during a year). The rate of failure increases each year a device is in use, ranging from 11 % failing the 1st year to more than 20 % failing by year 5. Moreover, by the end of year 5, 61 % of the surveyed notebooks had a failure that requiring repair (IDC, 2016).

IDC also reported the components most often damaged in notebooks, such as the screen, followed by the keyboard, then the data storage drive (HDD or SSD) and the battery (Figure 1). These outcomes are also confirmed by a former IDC study (2010), which shows that nearly 20 % of the notebooks have to be repaired due to a physical failure (14,2 %) or due to damage from accidents (9.5 %) every year (IDC, 2010). In that survey, the majority of respondents with damaged notebooks reported that they suffered damaged keyboards, followed by damage to the display screen. Non-exposed parts most prone to damage include batteries and HDDs, both cited by over half of the respondents (IDC, 2010).

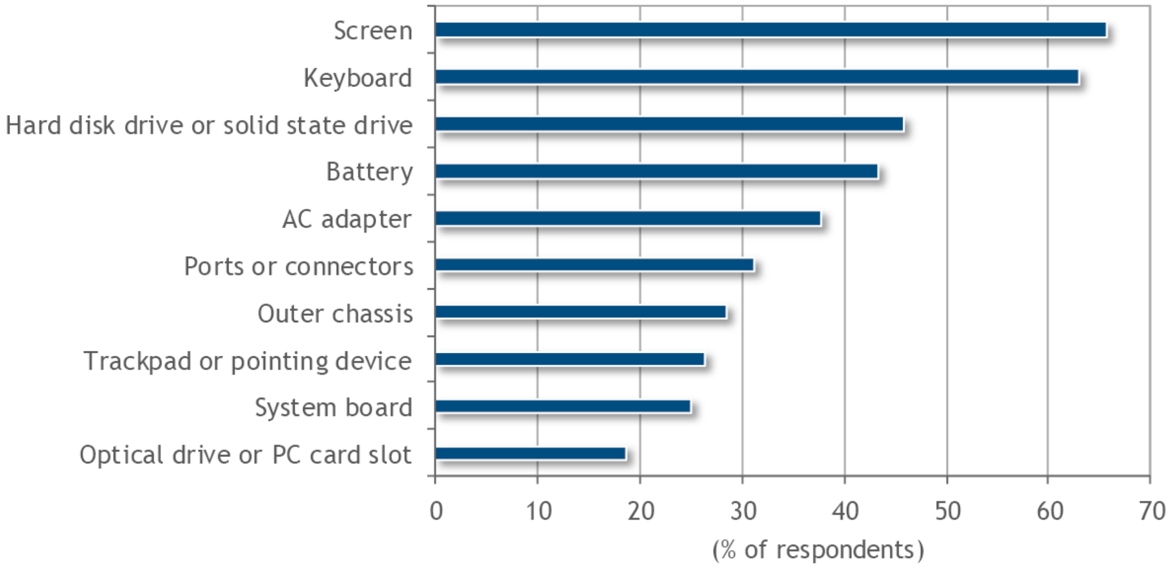

Figure 1 — Most common components in notebooks that suffered damage or breakage (IDC, 2016).

Other sources are available in literature. For instance, the insurance company SquareTrade analysed failure rates for over 30 000 new notebook computers covered by notebook warranty plans, in 2009. Looking at the first 3 years of ownership, 31 % of notebook owners reported a failure to SquareTrade. Two thirds of this failure (20.4 %) came from hardware malfunctions, and one-third (10.6 %) was reported as accidental damage (SquareTrade, 2009).

According to interviews conducted by Prakash et al. (2016a), four out of four repair operators stated that batteries and HDDs of consumer and business notebooks fail (very) frequently. The display, display cover (including frame joints) and the casing of consumer notebooks break frequently according to three repair service companies for consumer notebooks, whereas for business notebooks this does not seem to be the case (Prakash et al., 2016; Private communications, 2016).

Repair and reuse operators also observed that the following changes in the manufacturing of new notebooks characterised by compact design could influence the lifetime of the product, as the ability to repair or upgrade the devices is limited (Bölling, 2016; Prakash et al., 2016):

- built-in batteries;
- soldered-in memories;
- built-in mass storage;
- built-in (wireless) network boards;
- small connectors.

In conclusion, the slimmer and lighter the devices are designed and manufactured, the more integrated their components are and, as a consequence, the more difficult their replacement becomes (Tecchio et al., 2018).

2.2. Interviews

Two distinct facilities for product’s repair/reuse/refurbishing were visited to obtain better insight into the adopted processes, the available infrastructure and tools, and especially the challenges faced by operators. The two separate facilities are De kringwinkel Hageland located in Tienen, Belgium and Arrow Value Recovery located in Mechelen, Belgium. To share with the reader the main insights obtained during these visits a short description, illustrated with pictures of the process of both plants, is included in this section.

2.2.1. Reuse and repair processes at De Kringwinkel Hageland

De Krinwginkel Hageland is a non-profit organisation and is one of the nine reuse and repair centres represented by the Komosie group. Komosie offers job opportunities to in total 5 353 people in Flanders and focuses on the recruitment of people that have difficulties finding a job. The Komosie group has in total 125 shops in Flanders which sold more than 5.6 million products in 2015, of which 28 % were electrical and electronic equipment. The products repaired by De Kringwinkel Hageland are obtained from households and companies as donations, which were either brought to the premises of the reuse and repair centre or picked up by the organiszation at households or company premises.

All goods received by De Kringwinkel Hageland are first visually inspected and sorted based on their potential reuse value. Afterwards, products are further tested and, if required, technically feasible and economically viable, the products are repaired at dedicated work stations. Examples of products treated by De Kringwinkel Hageland are small domestic appliances, washing machines and washer-dryers, dishwashers, air conditioning units and ICT products. If the product is considered to be irreparable, the reusable parts are disassembled and stored in a warehouse, as shown in Figure 2.

The number of notebooks repaired by De Kringwinkel Hageland is currently limited because the performance of most notebooks they receive is too low to run the available operating system (Microsoft® Windows 10). When a notebook is reused or repaired, the HDD or SSD is always disassembled and wiped with open-source software for data deletion, on the work station shown in Figure 3. After preparation for reuse, every product is turned on and operated for a long period to ensure that it is working correctly.

Figure 2 — Spare parts warehouse at De Kringwinkel Hageland containing components that were disassembled from WEEE to be used for repair.

Figure 3 — Data deletion system, repair workbench and testing station for reused and repaired electronics at De Kringwinkel Hageland.

2.2.2. Repair and refurbishing processes at Arrow Value Recovery

Arrow Value Recovery owns and operates facilities around the world that repair and refurbish all kinds of IT infrastructure. One facility of the Arrow group is located in Mechelen. Arrow Value Recovery either buys used IT infrastructure and resells it to both individuals and businesses or provides repair and refurbishing services to companies that have a large number of used electronics, for example companies in the process of a new IT infrastructure rollout.

Most used IT equipment enters the facility in boxes packed on pallets. All products are unpacked, the content of every pallet is verified and all products are labelled with an individual barcode. During the unloading, a first sorting is performed based on the potential market value of the product. All products that are considered suitable for repair or refurbishing are put on a conveyor belt, which serves as a buffer for the other work stations, as shown in Figure 4.

Figure 4 — Warehouse, unloading workstation and transportation system for products to the other workstations for repair and refurbishing.

As a first step of the repair and refurbishing process, all notebooks are connected to a computer system, which performs a system check to gather information on the components present in the notebook and their condition, such as the size of the HDD and the number of damaged partitions, as shown in Figure 5. If the notebook is still operational, all data on the HDD or SSD is deleted multiple times to ensure all data is permanently removed. When the computer system indicates that the data deletion has been successfully completed, an operator completes a checklist to evaluate both the technical and aesthetic performance of the notebook.

Afterwards, the results of the performed tests are registered in the company’s database by another operator. If required, the notebook will be disassembled to either ensure that the technical specifications, such as RAM and HDD or SSD size, meet the expectations of potential customers, or to repair the product in case a problem was detected. If it is no longer economically viable to repair the notebook, all functioning components that could be used as spare parts are disassembled and stored in a warehouse.

Figure 5 — Repair and refurbishing process at Arrow Value Recovery in Mechelen.

2.2.3. General findings based on facility visits

Substantial differences in the ease of disassembly are acknowledged by all people interviewed between product brands and individual products. Complete disassembly is rarely performed. Therefore, it is crucial to evaluate the ease of partial disassembly taking into account the probability that a component will fail and need to be accessed and/or replaced. The time and the effort involved in accessing and/or disassembling and reassembling the failed component are considered as crucial and largely influence the potential reparability of the product. Components that are commonly disassembled because of failures or because they can be harvested as potential spare parts are: SSD or HDD, RAM memory, batteries and screen.

Each operator carrying out disassembly operations has access to a computer with internet access, which enables them to easily retrieve online disassembly instructions and repair guidelines. Some operators confirmed that they regularly use such guidelines. Most disassembly tasks on notebooks are performed with a plastic *spudger* (Figure 6) and a set of small screwdrivers that can be operated by finger movements.

Some common reasons why notebooks are not repaired are: they cannot be updated to the latest version of the operating system; the sourced notebooks are too old or have too low a performance level; the damaged components cannot be replaced in a cost-efficient manner due to the unavailability (or high cost) of spare parts, and/or disassembly and reassembly would take too much time and effort and the associated labour costs are too high.

Both organisations indicated that the demand for reused, repaired and refurbished notebooks is higher than their capacity, as their operations are limited by the limited number of (reparable) notebooks that they can obtain.

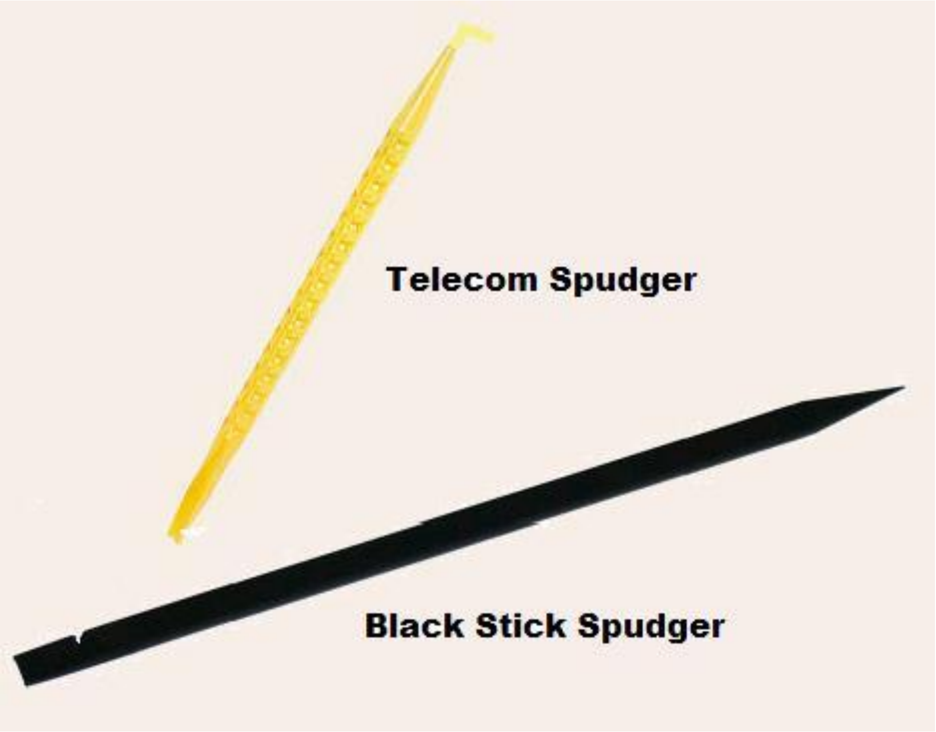

Figure 6 — Spudgers (credits: Michael Anderson, 2006)

2.3. Exploratory analysis on computer disassembly

In addition to the analysis of the literature and the interviews conducted with relevant stakeholders, the authors also performed a series of disassembly experiments to understand how to further develop the method, by adding relevant sequences. This analysis was particularly useful for identifying which types of connectors, or disassembly actions, needed to be added to the database, in order to properly assess eDIM on currently available notebook computers. The experiments were also useful in identifying possible difficulties that can arise when disassembling and reassembling a notebook.

A total of 39 notebooks were sourced from a WEEE collection centre in Ireland, in order to perform an experimental analysis of the disassembly time for the main components of notebooks for the purpose of reuse and repair.

The disassembly operations were undertaken by an experienced researcher who disconnected all fasteners in a non-destructive manner either by hand or using manual tools (e.g. spudgers and screwdrivers with a set of screw heads commonly required for computer and smartphone repair).

The disassembly of the notebooks typically started with the battery removal. Afterwards, the data storage drive (HDD or SSD) was extracted, which in most cases involved disassembling a hatch that was attached either by a snap fit or one to three screws. Once the data storage drive was extracted, the motherboard was then disassembled from the product housing. Finally, the LCD module was disassembled from the screen housing. The disassembly process was video recorded for all 39 notebooks. All the videos were analysed and the total time taken to extract the main components was registered, including the time needed for all unsuccessful attempts to release the components.

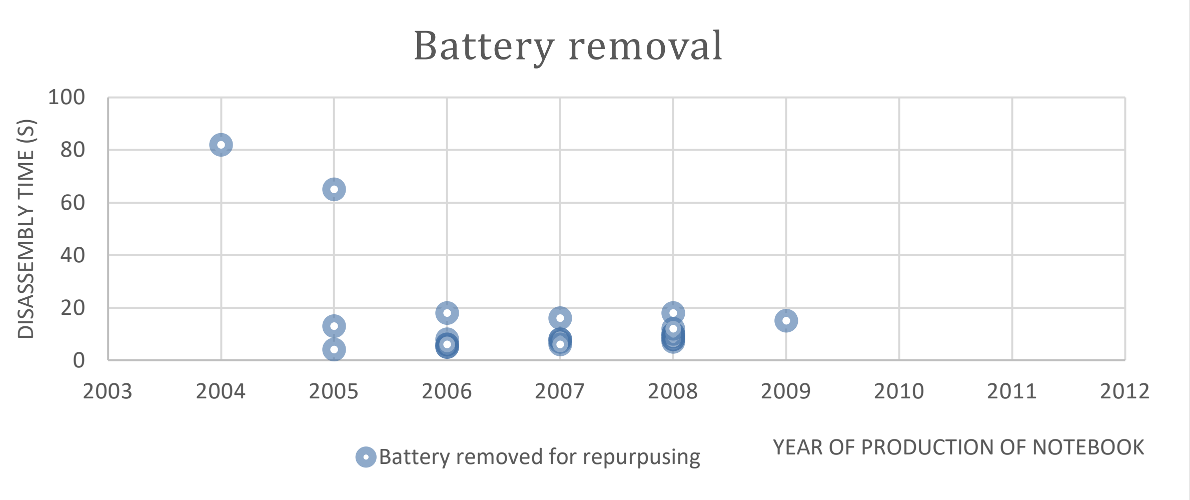

Figure 7 — Disassembly time analysed for the batteries of notebooks for repurposing.

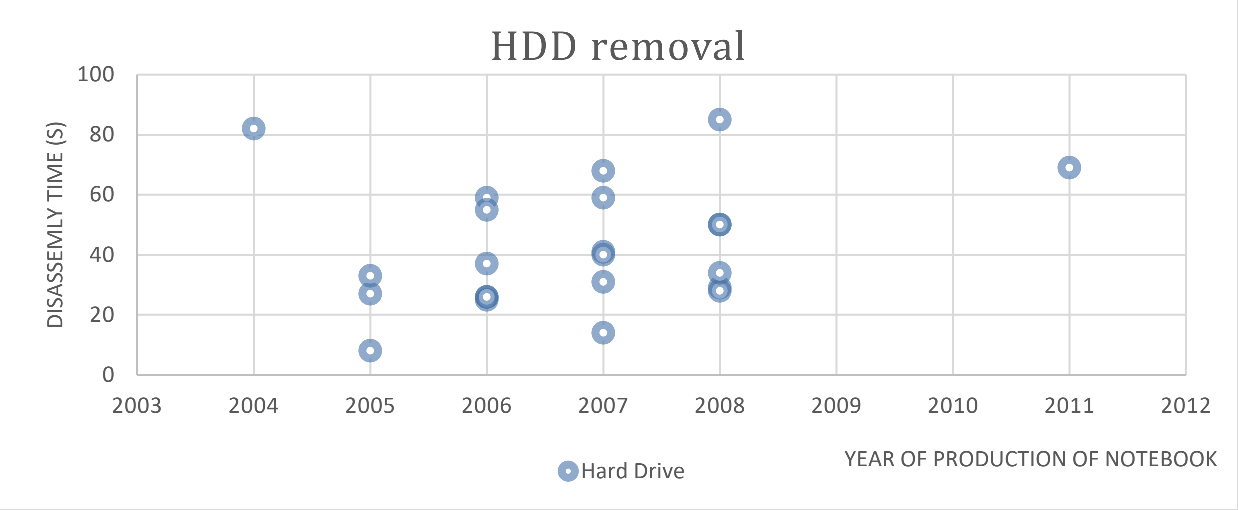

Figure 8 — Disassembly time for HDDs of notebooks for repurposing.

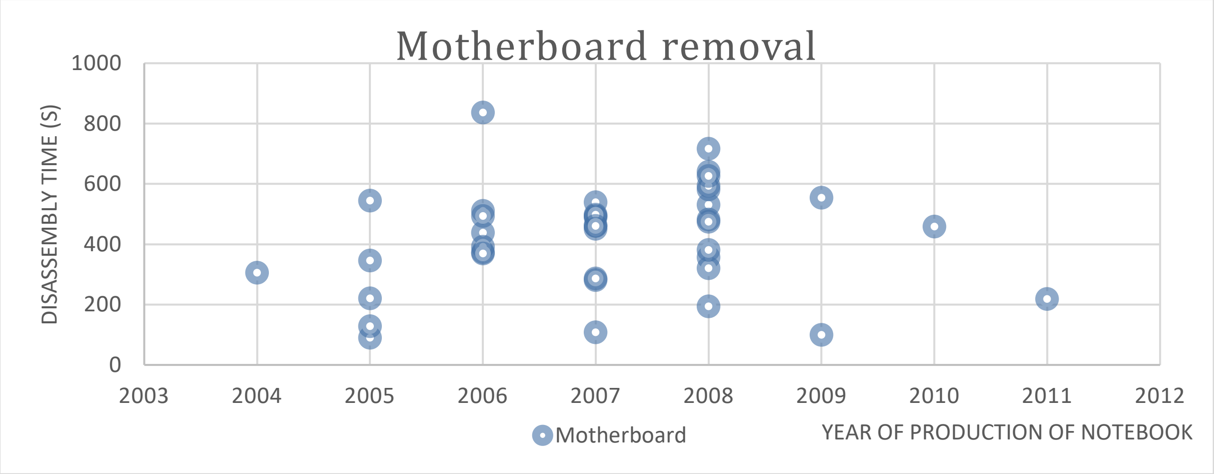

Figure 9 — Disassembly time for motherboards of notebooks for repurposing.

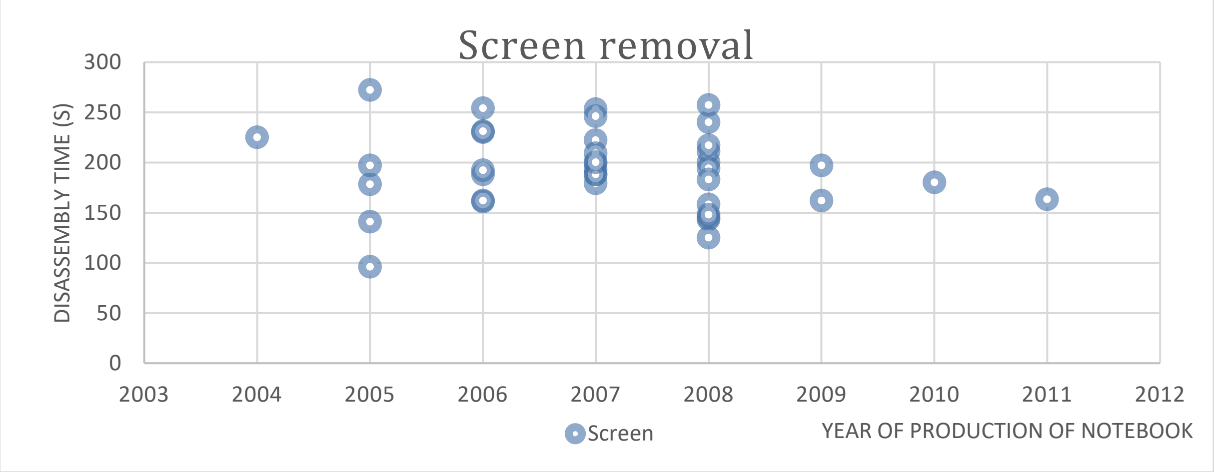

Figure 10 — Disassembly time for the screen of notebooks for repurposing.

The times shown in Figure 7 indicate only a minor difference in the effort required to disassemble the batteries from notebooks for the purposes of repair, except for two specific notebooks. These two notebooks (from 2004 and 2005) had a battery that could only be disassembled after disassembling the product housing. It should be noted that notebooks with a glued in battery were not analysed in this study, since glued-in batteries were not used in models commercialised in the past. However, since 2010, more and more notebooks have been equipped with a battery that can only be disassembled after removing the product housing or with a glued-in battery. Accordingly, the possible variation in the time needed to disassemble notebook batteries can be expected to further increase for models made after 2010.

Furthermore, based on the performed analysis, a significant variation in the disassembly times could be found for all notebooks for the batteries (4-82 s), HDDs (8-85 s), motherboards (90-836 s) and screen (96-272 s), as shown in Figure 7, Figure 8, Figure 9 and Figure 10. No significant trend could be determined in the disassembly time for the analysed components, which could also be due to the limited range of production years of the analysed notebooks that were all produced before 2011, the limited sample size and/or the high variation in disassembly times.

However, these results showed that it is possible to manufacture notebooks from which the main components, being batteries, HDDs or SSDs, motherboards and LCD modules, can be easily disassembled, whereas for most of the analysed notebooks it was still relatively time intensive to disassemble these components. In addition, as there is no clear trend in the presented data or in the industry in general, there is no indication that notebooks are becoming easier to disassemble.

The experiments performed confirmed the information collected through the literature review and the interviews with stakeholders. As outcomes, it is possible to highlight that:

- the eDIM may be contextualised to assess the partial disassembly of specific key components, such as the battery, HDD or SSD, LCD module and motherboard;
- new connection types should be added to the database, in particular cable connectors, cable plugs and adhesives;
- handling small connectors requires particular care, therefore additional time should be taken into account for handling connectors with a reduced dimension;
- tools that are not commonly available may be needed to disassemble certain products (8);
- certain connectors that look the same and fasten the same components may actually be different (e.g. screws with different length), so they should be labelled or properly registered to facilitate reassembly.

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(8) According to Recchioni et al. (2016), only commonly available tools should be allowed to be used during the extraction process. The set of acceptable tools should be defined in accordance with available ISO standards.

3. Further development of the eDIM method

The ease of disassembly method eDIM was further developed to take into consideration both disassembly and reassembly. Nonetheless, new disassembly (and reassembly) sequences were added in the database. To differentiate the metrics we refer to the following.

- eDIM: ease of disassembly metric calculated on the disassembly sequence and on the reassembly sequence. eDIM consists of the sum of two metrics:
- $eDIM_D$: ease of disassembly metric calculated on the disassembly sequence ('ease of disassembly metric');
- $eDIM_R$: ease of disassembly metric calculated on the reassembly sequence ('ease of reassembly metric');

The eDIM database has been set up using the MOST work measurement system method (Zandin, 2003). MOST can be employed to calculate the average time needed for every type of manual action that might be required during a (dis)assembly process. For the eDIM method, MOST was used to calculate the average figures representative of tool change, identifying connectors, positioning a tool relative to the connector, disconnecting different types of connectors and removing the released component. The average time needed for a specific action is calculated by summing up the figures representing individual basic motions for which the required times have been established by means of time and motion studies (9). These figures are compiled in different tables of the MOST methodology and are included in Appendix 1.

As the study aimed to evaluate the support of eDIM to standardisation activities, the method needed further development to address the following main topics:

1. the need to enlarge the eDIM database with other types of connectors, such as glues requiring wedge/pry and peel actions to be released;
2. the need to test the method on a broader range of products including small, portable electronics;
3. the need to explore ways to adapt eDIM for disassembly and reassembly.

In the work presented, case studies focus on notebooks. Furthermore, new connector types, such as adhesive and cable plugs with a hinge, were encountered compared to previous research that focused on electronic displays. These were considered for the population of the eDIM database. Most connections and components of the analysed notebooks were substantially smaller and more fragile, requiring more careful and precise handling. However, the manual handling needed to be performed for disassembly and reassembly was quite similar for most connections.

Based on the identified differences between previous and present case studies, several sequences of motions were added to the eDIM database to enable us to correctly apply eDIM to new case-study products such as notebooks, and to ensure that the calculated metric is representative for ease of disassembly and reassembly for the purposes of repair, reuse and remanufacturing. The required additions to the eDIM database are illustrated in this section.

3.1. eDIM database updated with reassembly values

The *Study for a method to assess the ease of disassembly of electrical and electronic equipment* (Vanegas et al., 2016) only focused on evaluating ease of disassembly, whereas ease of disassembly and reassembly are generally of equal importance during repair, reuse

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(9) For example, the disassembly task 'remove component' is decomposed in a series of standard motions: A1B0G1A1B0P1A1; where A1 represents a horizontal hand movement to a disconnected component within reach; B0, no vertical body movement; G1, gain control over the component; A1, move the component horizontally to a location within reach; B0, no vertical body movement; P1, place component within reach; and A1, return hands to the product. This sequence corresponds to 50 time measurement units (TMUs) and is equivalent to 1.8 seconds.

and remanufacturing operations. Therefore, reassembling figures were added to the eDIM database next to the releasing values per connection type.

The reassembling figures are determined in a similar manner as for the disassembly process for tool change, tool positioning, assembling (fastening) and adding components. The average figures determined by MOST for fastening and loosening several types of connections, such as screws, are the same. However, in most cases, several additional preparatory steps are required during reassembly. In addition, for most connectors, more care should be taken during the reassembly process. Therefore, the figures representing the reassembling of different types of connections is modelled separately using MOST, as further detailed in the next sections. The ease of disassembly metric and the ease of reassembly metric are calculated as follows:

- eDIM_D = tool change + identification + manipulation + tool positioning + disconnection + removal;
- eDIM_R = addition + tool change + identification + manipulation + tool positioning + fastening;

Finally, eDIM is the sum of eDIM_D and eDIM_R.

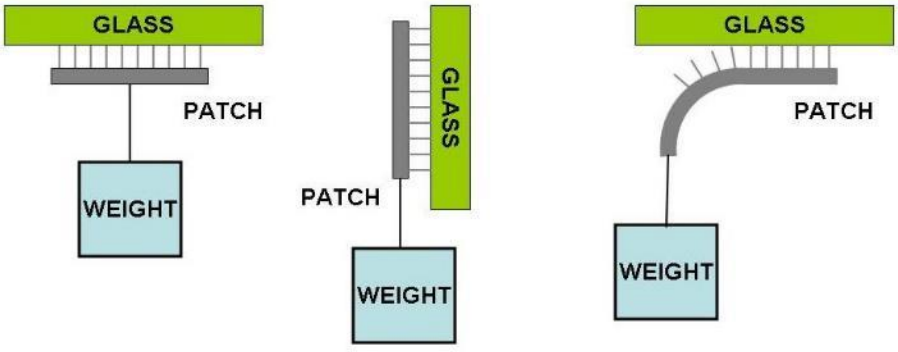
Definitions for tasks as 'tool change', 'identification', 'manipulation', 'tool positioning', 'disconnection' and 'removal' can be retrieved in the previous report devoted to the eDIM methodology (Vanegas et al., 2016, section 3.3). '**Fastening**' can be defined as the action of connecting a fastener (opposite of disconnection). '**Addition**' relates to the action of bringing and positioning a separated component to be assembled to the main product through connections and/or fasteners.

3.2. eDIM database updated with new connection types

The authors extended the database developed in prior research with some generally defined connector categories to limit the size of the database while maintaining a sufficiently high accuracy of the estimated disassembly and reassembly metrics. For the definition of these categories, the main aspect taken into consideration was the type of manual handling that is required to disassemble and reassemble a specific connector.

In accordance with this objective, a differentiation was made between **cable connectors** which can be pulled out manually with one hand with a force of less than 5 N, as were encountered in both monitors and notebooks, and cable connectors that need to be opened first by turning or bending a lever or snap-fit connection and can only be pulled out afterwards with one hand with a force of less than 5 N, as are also commonly found in notebooks. For the **cable plugs** category, a further distinction was made between cable connectors that can be manually disassembled and those that require the use of a sharp tool, referred to in this study as a 'spudger'. See section 0, Correction factors for handling of small connectors, for how to distinguish whether a tool needs to be used to release small connectors, such as cable plugs with a lever. If a substantially larger force or different type of movement is required to release other types of cable plugs, this could be a reason to include additional categories in the eDIM database.

Furthermore, **adhesives** were encountered in the two analysed notebooks. Adhesives are nowadays commonly applied in small electronic equipment and are also commonly released for repair purposes, as demonstrated in many online repair guidelines. Adhesives can be released in different manners by either applying a pull-off force, shear force or peel-off force, as shown in Figure 11. The disassembly of adhesives can also require the use of non-conventional tools, such as a spudger, opening pics, and/or the application of heat with, for example, a heat gun. Accordingly, depending on the type of adhesive, distinct manual motions are also required during disassembly and reassembly and the time required to perform these motions can differ substantially.



Pull-off test Pure shear test Peeling test

Figure 11 — Graphical illustration of difference between pull-off, shear and peeling forces (Project, 2014).

The following 4 generic categories of adhesive connectors are proposed, based on the different set of movements that need to be performed to release them.

- **Adhesive with < 5 N peel-off force**: adhesive that can be easily peeled-off manually with a peel-off force of less than 5 N when a flexible component such as a cable is removed. It should be stressed that a peel-off force can only be applied when one of the two components is sufficiently flexible and can be shaped with a small radius, as shown in Figure 12. This radius could be determined to be less than 5 mm diameter, without losing the full functionality of the component. There are different standards and specialised testing equipment which can be used to determine the 90- or 180-degree peel-off force of, for example, pressure sensitive tape, such as the harmonised international standard PSTC 101, the 180° peeling test for adhesive tapes ISO 29862:2007 (JIS Z 0237:2009), DIN EN 1939 edition 1996, ASTM-D3330 — A — Standard test method for peel adhesion of pressure-sensitive tape and ASTM-D3330 — B — E — Standard test method for peel adhesion of pressure-sensitive tape.

90° Peel **180° Peel**

Figure 12 — 90° and 180° peel-off forces applied to a flexible component attached by adhesive.

- **Adhesive with < 5 N pull-off or shear force**: adhesive that can be easily destroyed by pulling apart the attached components in the direction perpendicular to the adhesive or in the same direction as the adhesive. Since adhesives are rarely adopted to resist pull-off forces, they are also seldom characterised by a pull-off test, as shown in Figure 11. Consequently, no relevant standards were identified to evaluate the maximum pull-off forces for adhesives. In contrast, in all analysed specification sheets of adhesive tapes, the maximum shear force could be found often depending on the material to which the adhesive is bonded. Several standards also exist to evaluate the shear force for adhesives, such as the DIN EN 1939 edition 1996, the D4562 — 01(2013) Standard test method for shear strength of adhesives using pin-and-collar specimen and the ISO 10123:2013 Adhesives — Determination of shear strength of anaerobic adhesives using pin-and-collar specimens standard. Since the manual operations are the same for disconnecting an adhesive by shear or pull-off forces and because the adhesive will in most cases be released in the direction in which the adhesive is the weakest, it is proposed to use the minimum of the pull-off or shear force of the adhesive connection as a criteria to evaluate whether the connection belongs to this category or the next one.

- **Adhesive with > 5 N pull-off or shear force/5 cm**: For adhesives that require a pull-off force higher than 5 N, the use of several spudgers and/or opening pics is necessary to apply sufficient force while avoiding breaking components attached with the adhesive. Since the number of times spudgers or opening pics need to be used depends on the length of the adhesive, the eDIM value estimated for disassembling the adhesive is calculated per 5 cm of the nominal length of the adhesive.
- **Temperature-reversible adhesive/5 cm**: For adhesives that need to be heated up before they can be disassembled by placing spudgers or opening pics between the attached components, additional time should be taken into account for the heating. Since in most cases the components that are attached by the temperature-sensitive adhesive or that are in the proximity of this adhesive cannot resist high temperatures, only a relatively low-energy heat source can be applied, which results in a slow heating process.

The average values representing disassembly and reassembly actions can be found in Appendix 2, while the ease of disassembly and reassembly metrics per connection category are shown in Section 3.8.

3.3. Correction factors for handling small connectors

A greater effort is needed when positioning a tool to remove small connectors. To take this into account in the eDIM figures for disassembly, a specific correction factor for positioning requiring care or precision is defined for connections with an acting surface of less than 3 mm in diameter. This acting surface, such as the lever of a small cable plug or the head of a small screw, should be easily accessible in the direction that forces need to be applied to easily disconnect the connection. Therefore, a connection is also considered small when something obstructs access within 5 mm perpendicular to the acting surface area.

In addition, it is assumed that for smaller screws, hand tools are typically used instead of power tools during reuse, repair or remanufacturing operations, as the risk of damaging the product or fastener with a power tool is too high. This assumption was confirmed during the plant visits described earlier in this report. Furthermore, the correction factors for reassembling smaller screws with a more precise and careful positioning of the screw on the product or the screwdriver are included in the eDIM database.

3.4. Correction factors for assembly and/or fastener replacement

Depending on the type of adhesives used, in some cases a new adhesive will need to be applied to reassemble a product. To take this into account, correction factors have been included in the eDIM database for the effort needed to take a new adhesive, loosen it from its packaging and position it with high precision.

3.5. Correction factors for manipulating large or small appliances

Since the ease of disassembly metric and the ease of reassembly metric are based on the type and number of required manual operations, the eDIM method can be applied for the disassembly and reassembly of all sizes of products. It should only be considered that the effort required to manipulate the product to access the fasteners or components might vary substantially, as different types of manual operations have to be performed depending on the product size. In addition, it should be taken into account that for heavy products it is often more convenient for the operator to move around the product than to manipulate the product. To take this into account, the following categories of manipulation have been included in the eDIM database: manipulation by turning the product with one hand (product mass < 2kg — work bench); manipulation by turning with two hands (2kg < product mass < 4kg — work bench) and walking to another side of the product (operator kneeling down).

3.6. Correction factors for labelling connection types (optional CF1)

When a component is fastened by multiple connectors of different categories, additional effort is required for putting down the tool used previously and picking up a different tool. The values for tool change are automatically set within eDIM, depending on the tool required to disassemble the listed connectors. However, a common problem encountered during the reassembly process is that similar screws which require the same tool but have a different length are mixed up and reassembled in the wrong position, causing components to fail or not be properly reassembled. To prevent such errors during the reassembly process, well-illustrated guidelines are essential. Alternatively, in addition to placing every disassembled connector together with the disassembled component, the origin or destination of every screw type can be registered on the product by the manufacturer or by the user by making small annotations during the disassembly process, or by keeping each screw type in a different place. If the manufacturer uses different lengths of screws without providing clear markings on the product, additional manual operations are required to look up the correct position of every connector or to make annotations on the origin of every screw. Therefore, for every screw type, a category of '**screws same/component**' and '**screws different/component**' is included in the eDIM database. For the category of 'screws different /component', a correction factor is included to register the origin of the fastener.

A similar issue is commonly encountered for **cable connections**. It can be time-consuming to retrieve the correct position of every cable during reassembly if the cable is longer than 30 mm; otherwise the possible options for incorrect reassembly are limited. Therefore, for cable plugs, an 'unlabelled' category and a 'labelled' category have been included in the eDIM database. As for screws of different lengths, correction factors for marking connectors and cables are included for the category of unlabelled cable plugs.

3.7. Correction factors for fetching non-commonly available tools (optional CF2)

For one of the presented case study products, a 5-point pentalobe screwdriver was required. In both plants that were visited as part of this research, the required 5-point pentalobe screwdriver was available, but it was only available in a specific place and most operators would need to leave their work bench to go and get this tool and bring it back after using it. This experience also proves that the need for 'uncommon' tools (e.g. proprietary tools, or those for which specific standards have been not developed yet) would imply extra effort for disassembly.

Accordingly, the authors are convinced that when relevant, the additional effort for finding or sourcing a dedicated tool should also be reflected in the eDIM calculation. Therefore, for the pentalobe screwdriver, a correction factor was modelled taking into account the effort needed for a set of actions (standing up, walking 30 meters to a warehouse and back, taking the tool from a shelf, sitting down again and bringing it back when no longer needed). The inclusion of a correction factor for fetching non-commonly available tools is included in the eDIM database for disassembly sequences. However, it is only included in the calculation sheet as an optional parameter.

3.8. Sequences added to the eDIM database

Considering the further developments discussed earlier in Chapter 3, we have summarised and listed the main disassembly and reassembly sequences added to the eDIM database below.

- Cable connectors:
    - which can be pulled out manually with one hand with a force of less than 5 N;
    - that need to be opened first by turning or bending a lever or snap-fit connection and can only be pulled out afterwards with one hand with a force of less than 5 N, and which possibly require the use of a sharp tool, referred to in this study as a 'spudger'.
- Adhesives:
    - with < 5 N peel-off force;
    - with < 5 N pull-off or shear force;
    - with > 5 N pull-off or shear force/5 cm;
    - temperature-reversible adhesive/5 cm.

Other significant updates included in the eDIM database concern:

- the availability of **reassembly values** related to all the disassembly sequences already included;
- the availability of **correction factors**, for taking into account the effort needed in particular situations:
- for handling small connectors;
- for manipulating large or small appliances.
- the availability of **optional correction factors**, for taking into account the effort needed in particular situations:
- for labelling connection types;
- for fetching non-commonly available tools.

In particular, concerning **cable plugs**, the sequences for disassembling and reassembling are based on the effort needed to release the plug and/or the lever either by hand (finger manipulation) or with the use of a spudger.

For **adhesives**, finger manipulation is also considered for forces < 5 N, and two-hand manipulation for the use of opening pics or spudgers to release an adhesive with > 5 N pull-off or shear force. Furthermore, for the careful heating of adhesive tape, a time of 30 seconds per 5 cm nominal length of tape is taken into account.

New connection categories can always be added to the eDIM database in the future, by using the MOST methodology to define the individual movements (and therefore disassembly and reassembly values) needed for the disassembly and reassembly sequences.

Table 1 — eDIM values per disassembly per connection type. Optional CF1 = optional correction factors for labelling connection types. Optional CF2 = optional correction factors for fetching non-commonly available tools.

Connector type characteristics	Tool	Tool change(s)	Tool positioning(s)	Disassembly MOST sequence	Disassembly TMU	Disassembly(s)	eDIM value(s)	eDIM value(s) + optional CF1	eDIM value(s) + optional CF2
Screws same/component or labelled D < 3 mm and L < 3 mm	Philips screwdriver #1	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|	90.0	3.24	7.20	7.20	7.20
Screws same/component or labelled D < 3 mm and L < 3 mm	5-point pentalobe screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|	90.0	3.24	7.20	7.20	117.36
Screws same/component or labelled D < 3 mm and L < 3 mm	Torx T5 screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|	90.0	3.24	7.20	7.20	7.20
Screws same/component or labelled D < 3 mm and L < 3 mm	Philips 00 screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|	90.0	3.24	7.20	7.20	7.20
Screws same/component or labelled D < 3 mm and L < 3 mm	Torx T8 screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|	90.0	3.24	7.20	7.20	7.20
Screws different/component D < 3 mm and L < 3 mm	Philips screwdriver #1	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|+|R6|	90.0	3.24	7.20	17.28	7.20
Screws different/component D < 3 mm and L < 3 mm	5-point pentalobe screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|+|R6|	90.0	3.24	7.20	17.28	117.36
Screws different/component D < 3 mm and L < 3 mm	Torx T5 screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|+|R6|	90.0	3.24	7.20	17.28	7.20

Connector type characteristics	Tool	Tool change(s)	Tool positioning(s)	Disassembly MOST sequence	Disassembly TMU	Disassembly(s)	eDIM value(s)	eDIM value(s) + optional CF1	eDIM value(s) + optional CF2
Screws different/component D < 3 mm and L < 3 mm	Philips 00 screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|+|R6|	90.0	3.24	7.20	17.28	7.20
Screws different/component D < 3 mm and L < 3 mm	Torx T8 screwdriver	1.44	2.52	5*|L1|+ |A1B0G1|+ |A1B0P1|+|R6|	90.0	3.24	7.20	17.28	7.20
Cable plug labelled or L < 6 mm with lever and force < 5 N & D < 3 mm	Spudger	1.44	2.52	|L1|+|L1|	20.0	0.72	4.68	4.68	4.68
Cable plug unlabelled with lever and force < 5 N & D < 3 mm	Spudger	1.44	2.52	|A1B0G1|+|R1|+|A1B0P1| +|L1|+|L1|	20.0	0.72	4.68	6.48	4.68
Cable plug labelled or L < 6 mm without lever and force < 5 N & D < 3 mm	Hand	0	2.52	|L1|	10.0	0.36	2.88	2.88	2.88
Cable plug unlabelled without lever and force < 5 N & D < 3 mm	Hand	0	2.52	|A1B0G1|+|R1|+|A1B0P1|+ |L1|	10.0	0.36	2.88	4.68	2.88
Cable plug labelled or L < 6 mm with lever and force < 5 N & D > 3 mm	Hand	0	1.44	|L1|+|L1|	20.0	0.72	2.16	2.16	2.16
Cable plug unlabelled with lever and force < 5 N & D > 3 mm	Hand	0	1.44	|A1B0G1|+|R1|+|A1B0P1| +|L1|+|L1|	20.0	0.72	2.16	3.96	2.16
Cable plug labelled or L < 6 mm without lever and force < 5 N & D > 3 mm	Hand	0	1.44	|L1|	10.0	0.36	1.80	1.80	1.80
Cable plug unlabelled without lever and force < 5 N & D > 3 mm	Hand	0	1.44	|A1B0G1|+|R1|+|A1B0P1|+ |L1|	10.0	0.36	1.80	3.60	1.80

Connector type characteristics	Tool	Tool change(s)	Tool positioning(s)	Disassembly MOST sequence	Disassembly TMU	Disassembly(s)	eDIM value(s)	eDIM value(s) + optional CF1	eDIM value(s) + optional CF2
Hinge with force < 5 N	Hand	0	1.44	|L1|	10.0	0.36	1.80	1.80	1.80
Hinge with force < 5 N	Spudger	1.44	1.44	|L1|	10.0	0.36	3.24	3.24	3.24
Hinge with 5 N < force < 20 N	Hand	0	1.44	|L3|	30.0	1.08	2.52	2.52	2.52
Adhesive with < 5 N peel-off force	Hand	0	2.52	|L1|	10.0	0.36	2.88	2.88	2.88
Adhesive with pull-off force < 5 N	Spudger	1.44	2.52	|L1|	10.0	0.36	4.32	4.32	4.32
Adhesive with pull-off force < 5 N	Hand	0	2.52	|L1|	10.0	0.36	2.88	2.88	2.88
Adhesive with pull-off force > 5 N/5 cm nominal length	Spudger	1.44	2.52	|L6|	60.0	2.16	6.12	6.12	6.12
Temperature-reversible adhesive > 5 N/5 cm nominal length	Spudger	1.44	2.52	|heat up = 30 s|+|L6|	8393.3	302.16	306.12	306.12	306.12
Loose fit with force < 5 N	Hand	0	1.44	|L1|	10.0	0.36	1.80	1.80	1.80
Loose fit with force < 5 N	Spudger	1.44	1.44	|L1|	10.0	0.36	3.24	3.24	3.24
Default if not in database: < 10 single-hand assembly or disassembly finger manipulations with force < 5 N	Hand	0	1.4	10* IL1I	100	3.60	5.04	5.04	5.04

Table 2 — eDIM values per reassembly time per connection type. Optional CF1 = optional correction factors (for reading self-written annotations).

Connector type characteristics	Tool	Tool change(s)	Tool positioning(s)	Assembly MOST sequence	Assembly TMU	Assembly(s)	eDIM value(s)	eDIM value(s) + optional CF1
Screws same/component or labelled D < 3 mm and L < 3 mm	Philips screwdriver #1	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6|	140.0	5.04	9.00	9.00
Screws same/component or labelled D < 3 mm and L < 3 mm	5-point pentalobe screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6|	140.0	5.04	9.00	9.00
Screws same/component or labelled D < 3 mm and L < 3 mm	Torx T5 screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6|	140.0	5.04	9.00	9.00
Screws same/component or labelled D < 3 mm and L < 3 mm	Philips 00 screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6|	140.0	5.04	9.00	9.00
Screws same/component or labelled D < 3 mm and L < 3 mm	Torx T8 screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6|	140.0	5.04	9.00	9.00
Screws different/component D < 3 mm and L < 3 mm	Philips screwdriver #1	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6| + |I1|	140.0	5.04	9.00	9.36
Screws different/component D < 3 mm and L < 3 mm	5-point pentalobe screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6| + |I1|	140.0	5.04	9.00	9.36
Screws different/component D < 3 mm and L < 3 mm	Torx T5 screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6| + |I1|	140.0	5.04	9.00	9.36
Screws different/component D < 3 mm and L < 3 mm	Philips 00 screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6| + |I1|	140.0	5.04	9.00	9.36
Screws different/component	Torx T8 screwdriver	1.44	2.52	5*|F1| + |A1B0G1| + |A1B0P6| + |I1|	140.0	5.04	9.00	9.36

Connector type characteristics	Tool	Tool change(s)	Tool positioning(s)	Assembly MOST sequence	Assembly TMU	Assembly(s)	eDIM value(s)	eDIM value(s) + optional CF1
D < 3 mm and L < 3 mm								
Cable plug labelled or L < 6 mm with lever and force < 5 N & D < 3 mm	Spudger	1.44	2.52	|F1|	10.0	0.36	4.32	4.32
Cable plug unlabelled with lever and force < 5 N & D < 3 mm	Spudger	1.44	2.52	|F1|+|I1|	10.0	0.36	4.32	4.68
Cable plug labelled or L < 6 mm without lever and force < 5 N & D < 3 mm	Hand	0	2.52	|F1|	10.0	0.36	2.88	2.88
Cable plug unlabelled without lever and force < 5 N & D < 3 mm	Hand	0	2.52	|F1|+|I1|	10.0	0.36	2.88	3.24
Cable plug labelled or L < 6 mm with lever and force < 5 N & D > 3 mm	Hand	0	1.44	|F3|	30.0	1.08	2.52	2.52
Cable plug unlabelled with lever and force < 5 N & D > 3 mm	Hand	0	1.44	|F3|+|I1|	30.0	1.08	2.52	2.88
Cable plug labelled or L < 6 mm without lever and force < 5 N & D > 3 mm	Hand	0	1.44	|F3|	30.0	1.08	2.52	2.52
Cable plug unlabelled without lever and force < 5 N & D > 3 mm	Hand	0	1.44	|F3|+|I1|	30.0	1.08	2.52	2.88
Hinge with force < 5 N	Hand	0	1.44	|F1|	10.0	0.36	1.80	1.80
Hinge with force < 5 N	Spudger	1.44	1.44	|F1|	10.0	0.36	3.24	3.24
Hinge with 5 N < force < 20 N	Hand	0	1.44	|F3|	30.0	1.08	2.52	2.52

Connector type characteristics	Tool	Tool change(s)	Tool positioning(s)	Assembly MOST sequence	Assembly TMU	Assembly(s)	eDIM value(s)	eDIM value(s) + optional CF1
Adhesive with < 5 N peel-off force	Hand	0	2.52	|A1B0G3| + |L3| + |A1B0P6|	140.0	5.04	7.56	7.56
Adhesive with pull-off force < 5 N	Spudger	1.44	2.52	|A1B0G3| + |L3| + |A1B0P6|	140.0	5.04	9.00	9.00
Adhesive with pull-off force < 5 N	Hand	0	2.52	|A1B0G3| + |L3| + |A1B0P6|	140.0	5.04	7.56	7.56
Adhesive with pull-off force > 5 N/5 cm nominal length	Spudger	1.44	2.52	|A1B0G3| + |L3| + |A1B0P6|	140.0	5.04	9.00	9.00
Temperature-reversible adhesive > 5 N/5 cm nominal length	Spudger	1.44	2.52	|A1B0G3| + |L3| + |A1B0P6|	140.0	5.04	9.00	9.00
Loose fit with force < 5 N	Hand	0	1.44	|F1|	10.0	0.36	1.80	1.80
Loose fit with force < 5 N	Spudger	1.44	1.44	|F1|	10.0	0.36	3.24	3.24
Default if not in database: < 10 single-hand assembly or disassembly finger manipulations with force < 5 N	Hand	0	1.44	10*IF1I	100	3.60	5.04	5.04

4. Case studies: notebook computers

The updated eDIM method was tested on an 11′′ notebook manufactured in 2011, referred to as notebook 1, and a 13.3′′ notebook from 2015, referred to as notebook 2. Notebook 1 was selected as a case study because of its compact design, production in large quantities and online availability of detailed disassembly and repair instructions. For notebook 1 the eDIM method was applied based on data retrieved from empirical experiments, as well as data for disassembly and repair obtained from the online disassembly instructions. Notebook 2 was selected as a case study because disassembly guidelines have been published by the manufacturer and it obtained a relatively high reparability assessment from a specialised company. For notebook 2 the eDIM method was applied based on data and disassembly guidelines provided by manufacturer and by online websites.

Before starting the disassembly process, notebook 1 and notebook 2 were assumed to be closed and laid down face down, as advised in most repair guides. For repairing electronic components, several precautions must be taken to prevent possible damage. It is generally advised to disconnect the battery as quickly as possible to avoid shorting out any components during the further disassembly of the product. The disconnection of the battery should therefore always be included in the disassembly sequence as early as possible.

Possible damage can also be caused by unwanted electrostatic discharge between the operator and a sensitive electronic component. To prevent the build-up of electrostatic currents in the operator, wearing special bracelets and shoes is advised.

4.1. Required disassembly tasks for the complete and partial disassembly of the case study notebooks

In Appendix 3, all the disassembly tasks required to completely disassemble notebook 1 are described based on the different repair instructions found on the Ifixit website and the practical experiments performed by the researchers. The title of each step also indicates the sequence in which the described steps have to be executed to replace a specific component. In Table 3, the disassembly sequence for notebook 1 based on these repair guidelines is shown. The detailed calculations for notebook 1 can be found in Appendix 5.

Table 3 — Disassembly sequence for notebook 1

Component code	Disassembly sequence of components	Disassembly sequence of connections of components	Connector type	Number of connectors	Number of manipulations	Identifiability (0, 1)	Tool type
1	Bottom Cover	2.5 mm 5-point Pentalobe screw	Screws different/component D < 3 mm and L < 3 mm	**8**	**0**	**0**	5-point Pentalobe Screwdriver
	Bottom Cover	8 mm 5-point Pentalobe screw	Screws different/component D < 3 mm and L < 3 mm	**2**	**0**	**0**	5-point Pentalobe Screwdriver
2	Battery	Cable plug	Cable plug labelled or L < 6 mm without lever and force < 5 N & D>3 mm	**1**	**0**	**0**	Hand
3	Battery	5.2 mm T5 torx screw	Screws different/component D < 3 mm and L < 3 mm	**2**	**0**	**0**	Torx T5 Screwdriver
	Battery	6 mm T5 torx screw	Screws different/component D < 3 mm and L < 3 mm	**1**	**0**	**0**	Torx T5 Screwdriver
	Battery	2.6 mm T5 torx screw	Screws different/component D < 3 mm and L < 3 mm	**2**	**0**	**0**	Torx T5 Screwdriver
	Battery	Hinge	Hinge with force < 5 N	**1**	**0**	**0**	Hand
4	Right speaker	Cable plug	Cable plug labelled or L < 6 mm without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	Right speaker	Adhesive	Adhesive with pull-off force > 5 N/5 cm nominal length	**2**	**0**	**0**	Spudger

Component code	Disassembly sequence of components	Disassembly sequence of connections of components	Connector type	Number of connectors	Number of manipulations	Identifiability (0, 1)	Tool type
5	Solid State Drive	2.9 mm T5 torx screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Torx T5 Screwdriver
	Solid State Drive	Hinge	Hinge with force < 5 N	**1**	**0**	**0**	Spudger
6	I/O board cable	Cable plug	Cable plug unlabelled without lever and force < 5 N & D >3 mm	**1**	**0**	**0**	Hand
	I/O board cable	adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	I/O board cable	Cable plug	Cable plug unlabelled without lever and force < 5 N & D >3 mm	**1**	**0**	**0**	Hand
7	Fan	Cable plug	Cable plug labelled or L < 6 mm without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	Fan	5.2 mm T5 torx screw	Screws different/component D < 3 mm and L < 3 mm	**2**	**0**	**0**	Torx T5 screwdriver
	Fan	3.6 mm T5 torx screw	Screws different/component D < 3 mm and L < 3 mm	**1**	**0**	**0**	Torx T5 screwdriver
8	I/O board	Cable plug	Cable plug unlabelled without lever and force < 5 N & D >3 mm	**1**	**0**	**0**	Hand
	I/O board	Cable plug	Cable plug unlabelled without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	I/O board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	I/O board	3.6 mm T5 torx screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Torx T5 screwdriver
9	Left speaker	Cable plug	Cable plug unlabelled without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	Left speaker	Adhesive	Adhesive with pull-off force > 5 N/5 cm nominal length	**2**	**0**	**0**	Spudger
10	Microphone	Loose fit	Loose fit with force < 5 N	**1**	**0**	**0**	Hand
11	Heat sink	2.5 mm T5 torx screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**4**	**0**	**0**	Torx T5 screwdriver
	Heat sink	Adhesive	Adhesive with pull-off force < 5 N	**1**	**0**	**0**	Hand
12	Trackpad	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Trackpad	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**1**	Spudger
	Trackpad	1.5 mm Phillips 00 screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**6**	**1**	**0**	Philips 00 screwdriver
13	Logic board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Logic board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Logic board	Loose fit	Loose fit with force < 5 N	**1**	**0**	**0**	Hand
	Logic board	Cable plug	Cable plug unlabelled without lever and force < 5 N & D < 3 mm	**2**	**0**	**0**	Hand
	Logic board	3.6 mm T5 torx screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**3**	**0**	**0**	Torx T5 screwdriver
14	Display	Adhesive	Adhesive with < 5 N peel-off force	**6**	**0**	**0**	Hand
	Display	T8 screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**4**	**1**	**0**	Torx T8 screwdriver

In Appendix 4, all the required disassembly tasks are described to completely disassemble notebook 2 based on the repair guidelines made available online by the producer. Where needed and when possible, these guidelines were complemented with online repair guidelines and the description of the product teardown on the Ifixit website. In Table 4, the disassembly sequence with all the information that is required to calculate the ease of disassembly and ease of reassembly is shown. The detailed calculations for notebook 2 can be found in Appendix 6.

Table 4 — Disassembly sequence for notebook 2

Component code	**Disassembly sequence of components**	**Disassembly sequence of connections of components**	**Connector type**	**Number of connectors**	**Number of manipulations**	**Identifiability (0, 1)**	**Tool type**
1	Lower case	Hinge system badge	Hinge with force < 5 N	**1**	**0**	**0**	Spudger
	Lower case	Tx5 screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**9**	**0**	**0**	Torx T5 Screwdriver
	Lower case	Hinge	Hinge with force < 5 N	**1**	**0**	**0**	Spudger
2	Battery	Cable plug	Cable plug labelled or L < 6 mm without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	hand
	Battery	M2*2	Screws same/component or labelled D < 3 mm and L < 3 mm	**3**	**0**	**0**	Philips screwdriver
	Battery	M1.6*4	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Philips screwdriver
3	Solid state drive	Philips screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Philips screwdriver
	Solid state drive	Loose fit	Loose fit with force < 5 N	**1**	**0**	**0**	Hand
4	Wireless card	Cable plug	Cable plug labelled or L < 6 mm without lever and force < 5 N & D < 3 mm	**2**	**0**	**0**	Hand
	Wireless card	Philips screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Philips screwdriver
	Wireless card	Loose fit	Loose fit with force < 5 N	**1**	**0**	**0**	Hand
5	Speakers	Cable plug	Cable plug unlabelled without lever and force < 5 N & D > 3 mm	**2**	**0**	**0**	Hand
	Speakers	Philips screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**4**	**0**	**0**	Philips screwdriver
	Speakers	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
6	Heat sink	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**4**	**0**	**0**	Philips screwdriver
	Heat sink	Heat paste	Adhesive with pull-off force < 5 N	**1**	**0**	**0**	Hand
7	Coin-cell battery	Cable plug	Cable plug labelled or L < 6 mm without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	Coin-cell battery	Adhesive	Adhesive with pull-off force < 5 N	**1**	**0**	**0**	Hand
8	Battery-status light cable	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	Battery-status light cable	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
9	Touch pad	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Touch pad	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	Touch pad	Philips screw	Screws same/component or labelled D < 3 mm and L < 3 mm	**4**	**0**	**0**	Philips screwdriver
	Touch pad	Hinge	Hinge with force < 5 N	**1**	**0**	**0**	Hand
10	I/O-board cable	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**2**	**0**	**0**	Spudger
	I/O-board cable	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand

Component code	Disassembly sequence of components	Disassembly sequence of connections of components	Connector type	Number of connectors	Number of manipulations	Identifiability (0, 1)	Tool type
11	I/O board	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**2**	**0**	**0**	Philips screwdriver
	I/O board	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	I/O board	Cable plug	Cable plug unlabelled without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	I/O board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
12	Keyboard control board	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	Keyboard control board	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	Keyboard control board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Keyboard control board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Keyboard control board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Keyboard control board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	Keyboard control board	Hinge	Hinge with force < 5 N	**1**	**0**	**0**	Spudger
13	Display assembly	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Philips screwdriver
	Display assembly	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	Display assembly	Cable plug	Cable plug unlabelled without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	Display assembly	Adhesive	Adhesive with < 5 N peel-off force	**1**	**0**	**0**	Hand
	Display assembly	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Philips screwdriver
	Display assembly	Cable plug	Cable plug unlabelled without lever and force < 5 N & D >3 mm	**1**	**0**	**0**	Hand
	Display assembly	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**4**	**1**	**0**	Philips screwdriver
	Display assembly	Hinge	Hinge with force < 5 N	**1**	**0**	**0**	Hand
14	System board	Adhesive	Adhesive with < 5 N peel-off force	**2**	**0**	**0**	Hand
	System board	Cable plug	Cable plug unlabelled without lever and force < 5 N & D < 3 mm	**2**	**0**	**0**	Hand
	System board	Cable plug	Cable plug unlabelled with lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Spudger
	System board	Adhesive	Adhesive with < 5 N peel-off force	**2**	**0**	**0**	Hand
	System board	Cable plug	Cable plug unlabelled without lever and force < 5 N & D < 3 mm	**1**	**0**	**0**	Hand
	System board	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**5**	**0**	**0**	Philips screwdriver
	System board	Hinge	Hinge with force < 5 N	**1**	**0**	**0**	Hand
15	Power-adaptor port	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Philips screwdriver
16	Fan	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**1**	**0**	**0**	Philips screwdriver
17	Keyboard	Screws	Screws same/component or labelled D < 3 mm and L < 3 mm	**30**	**0**	**0**	Philips screwdriver

5. Results

Before presenting the results, it is important to note that the objective of this study was not to compare the performances of the two analysed notebooks, nor to establish a preference. Rather, the objective was to determine the applicability of the eDIM method to different types of notebooks and to investigate whether the eDIM method allows to properly asses the ease of disassembly for these products.

In addition, it is highlighted that the eDIM is a metric to estimate the 'ease of disassembly and/or reassembly' of products and that values calculated for the presented case studies cannot be directly compared with measured disassembly and/or reassembly times. In fact, the eDIM method assumes that the operator knows all the required steps for disassembling and reassembling, and only performs the manual operations required for disassembly and reassembly.

5.1. Complete disassembly and reassembly calculations

Table 5 presents the results of the eDIM calculations, considering both complete disassembly (eDIM_D) and complete reassembly (eDIM_R) of notebook 1 and notebook 2. Calculations were initially made excluding the use of correction factors to label connectors and correction factors to fetch non-conventional tools. These aspects are analysed later, in Sections 5.3 and 5.4.

Table 5 — Complete disassembly and reassembly calculations for notebook 1 and notebook 2 excluding the additional effort required to source non-standardised tools and excluding the additional effort needed for labelling connections (totals may not add up because of rounding).

	Disassembly [s]							**Reassembly [s]**							**eDIM [s]**
	Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM_D Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM_R Reassembly(s)**	
Notebook 1	22	4	4	163	140	18	**350**	22	4	4	163	257	18	**466**	**816**
Notebook 2	27	0	2	283	253	24	**589**	27	0	2	283	451	24	**787**	**1376**

The differences between the ease of disassembly and ease of reassembly metrics are only due to the difference between disconnecting and fastening figures, as the reverse assembly sequence is considered for disassembly and because the tool change, identifying, manipulation, positioning, removing and adding times are the same in a disassembly and reassembly process. The main differences between disconnecting and fastening can be found in the case of cable plugs with a lever, which require one action to move the lever and a second action to pull out the cable, whereas they can be fastened with the single action of pushing in the cable. Similarly, adhesives can be released with the single action of pulling apart the fastened components, but for reassembly require two actions: carefully preparing and then reapplying. In contrast, more effort is needed for the disassembly process than the reassembly process when annotations have to be made during disassembly to prevent errors during reassembly.

The main differences between the metrics calculated for notebook 1 and notebook 2 are due to:

- the difference in product structure, which requires, in some cases, the disassembly of a large number of components to access the targeted component;
- the use of connectors for which the required tools to disassemble and reassemble are not commonly available;
- the use of adhesive instead of screws;
- the use of smaller screws;
- the lack of marking of the position of the cables;
- the use of screws of different lengths and/or the lack of marking of the correct position of the screws.

5.2. Partial disassembly and reassembly calculations

We note that the eDIM method can also be applied to partial disassembly and/or reassembly of products, as it is based on a predefined disassembly and/or reassembly sequence.

Table 6 and Table 7 present the results of the eDIM calculations, considering both the partial disassembly (eDIM$_D$) and the partial reassembly (eDIM$_R$) of notebook 1 and notebook 2, to extract, respectively, the **battery** and the **motherboard**. The battery is a key component for a notebook computer, as its durability is a key feature for users (Tecchio et al., 2018), and a survey among 300 organisations highlighted that 22 % of notebook computers required the purchase of a replacement battery during their lifetime (IDC, 2010). Previous studies and interviews with stakeholders also showed that the motherboard is crucial for product longevity. Nonetheless, according to Dodd et al. (2016; 2015), within the production phase of computers, specific components such as the motherboard can be identified as environmental 'hotspots'. Critical raw materials and precious metals such as silver, gold and palladium contained in the motherboard contribute to the relatively high impact in various environmental categories.

In this section, as well as in section 5.1, calculations have been made excluding the use of correction factors to label connectors and correction factors to fetch non-conventional tools.

Table 6 — Partial disassembly and reassembly calculations for the **battery** of notebook 1 and notebook 2 excluding the additional time required to source non-standardised tools and excluding the additional time needed for labelling connections.

	Disassembly [s]							**Reassembly [s]**							**eDIM [s]**
	Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM$_D$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_R$ Reassembly(ies)**	
Notebook 1	3	0	0	41	49	3	**96**	3	0	0	41	77	3	**123**	**219**
Notebook 2	6	0	0	38	43	3	**90**	6	0	0	38	67	3	**113**	**203**

Table 7 — Partial disassembly and reassembly calculations for the **motherboard** of notebook 1 and notebook 2 excluding the additional time required to source non-standardised tools and excluding the additional time needed for labelling connections (totals may not add up because of rounding).

	Disassembly [s]							**Reassembly [s]**							**eDIM [s]**
	Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM_D Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM_R Reassembly(ies)**	
Notebook 1	13	0	0	103	95	13	**224**	13	0	0	103	154	13	**283**	**507**
Notebook 2	19	0	0	98	84	8	**202**	10	0	0	98	150	8	**268**	**470**

As shown in Table 6, the eDIM associated with the disassembly and reassembly of notebooks for the battery is very similar for both case studies, as this is for both notebooks the first component that can be extracted after disassembling the lower case and because the types of connections that need to be disassembled and reassembled are highly similar. In contrast, the eDIM associated with the disassembly and reassembly of the motherboards in the two notebooks shows larger differences (Table 7). This can be explained by the different types of connections used and the different product structure, which means that for notebook 1 more components need to be disassembled than for notebook 2, such as the I/O printed wiring board, prior to disassembling the motherboard.

5.3. Optional — use of correction factors to label connectors

The results of Table 5 refer to the hypothesis that the operator knows all required steps for disassembling and reassembling, and only performs the manual operations required for disassembly and reassembly. The knowledge of the exact disassembly/reassembly sequence is indeed a pre-requisite of the eDIM method. However, during the disassembly and reassembly operations in a repair centre, difficulties could arise during the disassembly and reassembly process. Therefore, Table 8 provides the results of the eDIM calculations, considering both complete disassembly (eDIM_D) and complete reassembly (eDIM_R) of notebook 1 and notebook 2, where calculations include the use of correction factors for labelling connectors. This includes, for example, the extra effort needed for the repair operator to sort and make annotations about the type, origin or destination of unlabelled connections (e.g. screws).

Table 8 — Complete disassembly and reassembly calculations for notebook 1 and notebook 2 excluding the additional time required to source non-standardised tools and including the additional time needed for labelling connections (totals may not add up because of rounding).

	Disassembly [s]							**Reassembly [s]**							**eDIM [s]**
	Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM$_{D}$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_{R}$ Reassembly(ies)**	
Notebook 1	22	4	4	163	343	18	**553**	22	4	4	163	267	18	**477**	**1030**
Notebook 2	27	0	2	283	285	24	**621**	27	0	2	283	458	24	**794**	**1415**

Taking into account a correction factor for labelling connectors mainly increases the eDIM$_{D}$ for both notebooks, as it includes the effort for preparing annotations, for example. During the reassembly, on the other hand, only additional effort to read annotations is required. Accordingly, the eDIM$_{R}$ for both notebooks is less influenced by this factor.

By comparing the eDIM results shown in Table 8 to the eDIM results without the correction factor shown in table Table 5, it is possible to observe a minor difference in the eDIM for notebook 2, either because similar types of connections are used or because annotations are provided on the product itself (e.g. which connections types and cables have to be attached to which location). For notebook 1, however, there is a more consistent increase of the eDIM of about 214 seconds, as a significant number of annotations needs to be made for this notebook in order to avoid incorrect reassembly.

5.4. Optional — use of correction factors to fetch non-conventional tools

The eDIM calculation assumes by default that all the tools required for disassembly/reassembly are available to the operator. However, during the performed experiments and company visits it was noted that not all tools were available on the workbench of operators working at repair centres. Accordingly, in some cases, there may be extra effort required to go and get additional tools not available on the disassembly desk. Table 9 provides the results of the eDIM calculations, considering both complete disassembly (eDIM$_{D}$) and complete reassembly (eDIM$_{R}$) of notebook 1 and notebook 2, where calculations include the use of correction factors to fetch non-conventional tools.

Table 9 — Complete disassembly and reassembly calculations for notebook 1 and notebook 2 including the additional time required to source non-standardised tools and excluding the additional time needed for labelling connections (totals may not add up because of rounding).

	Disassembly [s]							Reassembly [s]							eDIM [s]
	Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM$_D$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_R$ Reassembly(ies)**	
Notebook 1	132	4	4	163	140	18	**460**	22	4	4	163	257	18	**466**	**926**
Notebook 2	27	0	2	283	253	24	**589**	27	0	2	283	451	24	**787**	**1376**

Compared to the calculated time without correction factors to fetch non-conventional tools (Table 5), only the total time for notebook 1 increases, as only this notebook contained 5-point pentalobe screws. Overall, the eDIM for notebook 2 in Table 9 is 110 seconds higher than the eDIM for notebook 2 of Table 5, which is a significant increase, as it includes the effort required to fetch a non-standard tool, therefore increasing the actual eDIM assessed in ideal conditions.

6. Discussion

All product lifetime extension strategies, such as repair, reuse and product harvesting for component reuse, require facilitated access to product components. Our visits to the reuse, repair and refurbishing facilities confirmed that ease of disassembly is one of the main factors determining the economic viability of their operations. In addition, prior research on available literature demonstrated that, on average, nearly 18 % of notebooks used in United States businesses break or require repair every year (IDC, 2016). This number was confirmed by insurance companies, which reported that 20.4 % of the more than 30 000 analysed notebooks had hardware malfunctions during the first 3 years of ownership (SquareTrade, 2009).

To increase the economic viability of a more circular economy, it is crucial to drive innovation to reduce the effort needed to access the internal components for inspection, maintenance, reuse, repair and refurbishing/remanufacturing.

The case studies presented demonstrate that the majority of information required to calculate ease of disassembly using the eDIM method is, to a large extent, already available in manufacturers' service manuals and websites, or in repair manuals or websites from independent private companies. The only information that was missing in some cases was a detailed description of the fasteners used, such as the screw type or the force required to release an adhesive, whereas this information is certainly also of value for the operators performing disassembly and reassembly tasks. The documentation required for calculating the ease of disassembly/reassembly metric would also be of value for repair, reuse and remanufacturing centres, as it contains all the information found in repair guidelines or service manuals.

6.1. Analysed case studies

For the present research, 39 notebooks (manufactured between 2004 and 2011) were sourced from a WEEE collection centre in Ireland in order to perform an experimental analysis of the disassembly. In addition, two case studies (notebook 1 and notebook 2, manufactured between 2011 and 2015) were analysed using the eDIM method. Both the ease of disassembly and the ease of reassembly were calculated for these two case studies, as reported in Chapter 5.

Clear differences between the two notebooks selected as case studies and the 39 notebooks used for the disassembly analysis were noted in the product architecture and types of connectors used. The main differences consist of the more frequent use of adhesives, smaller cable plugs and smaller screws for the more recent notebook 1 and notebook 2. In addition, for notebook 1 and notebook 2, nearly all components needed to be disassembled before the screen could be disassembled, whereas for the 39 notebooks, the screen could be disassembled without removing the motherboard in all cases. Furthermore, for both notebook 1 and notebook 2, the lower cover needed to be disassembled before the battery could be disassembled, whereas for most of the other 39 notebooks the battery could be disassembled by moving a single lever. Based on the analyses on the more recent notebooks, we could suppose that in the near future, disassembly and reassembly will become more difficult, making the repair, refurbishing and remanufacturing of notebook computers more complex. This trend was also confirmed by interviews with repair/reuse/refurbishing operators.

The evaluation of the ease of complete disassembly and reassembly indicated substantial differences between the two analysed notebooks. For partial disassembly and reassembly of the battery, the difference is minimal, whereas for the disassembly and reassembly of the motherboard there was a substantial difference, which can be explained by the difference in product architecture and types of connections used. Accordingly, the presented case studies demonstrate how the eDIM method can quantitatively evaluate the ease of disassembly and reassembly, pinpoint how specific design solutions affect the ease of disassembly and reassembly and hence differentiate between products with different performance rates.

When the additional time required to fetch non-standardised tools and the additional time needed for labelling connections are taken into account, there is an even more substantial difference in the ease of disassembly and reassembly. As the sourcing of non-standardised tools requires substantial effort, and because errors are possible during reassembly due to connections that look similar, the researchers believe that the use of these correction factors also reflects some additional problems encountered by small and medium-scale repair shops and customers performing repairs. In the case of large-scale and/or highly specialised repair shops, these correction factors might of course not be relevant, however such repair organisations have currently not been analysed by the authors of the study.

6.2. Insertion of new connection types into the eDIM database

Theoretically, everything that has been assembled by humans can be disassembled by humans. However, it is only relevant to calculate the ease of disassembly of a specific component when it is, from a technical and economic perspective, realistic that this component would be disassembled. Therefore, it could be argued that no metric can be calculated for connections made using glues or welding techniques which can never be undone with available tools and infrastructure, or if it would never be economically viable to disassemble such connections.

However, the ease of disassembly metric can always be calculated as long as there is a technical solution readily available to disassemble the component. As demonstrated in the presented case studies, eDIM can be used for any type of connection, as the values characterising a specific action are calculated depending on the individual basic motions. Once the basic motions are known, the reference values for the eDIM calculation can be retrieved in the different tables of the MOST method. The most relevant tasks of the MOST method for disassembly and reassembly are shown in Appendix 1.

Whenever a MOST value cannot be retrieved from the existing literature, it is possible to perform a study to determine the effort required for the specific motion, as described by the MOST method. Alternatively, it could also be decided that if specific types of connections cannot be categorised in the existing connection categories (e.g. when the sequence of motions required to disassemble or reassemble these connectors is substantially different), an additional category can be added to the database, with values that can be determined based on practical evidence delivered (e.g. by manufacturers or by a dedicated study).

To conclude, eDIM can be used to calculate the ease of disassembly for all types of new connectors with different types of tools: this provides the required flexibility to use eDIM as a generic method and potentially standardisable method.

6.3. Applicability of eDIM for partial disassembly and reassembly

During both plant visits, it was clear that complete disassembly is rarely performed. In the presented case studies, the assessment of complete disassembly is only calculated to demonstrate the applicability of the method to assess the ease of disassembly and the ease of reassembly for all components of both case study products. As demonstrated in the presented case studies, the ease of partial disassembly can always be calculated as long as the number, type and sequence of connections that have to be disassembled and reassembled are known. Accordingly, the eDIM method can also be used to assess the ease of disassembly and reassembly for repair purposes if a specific component needs to be accessed and/or replaced. Accordingly, allocation procedures while calculating the eDIM are not necessary, since the method refers to the (disassembly and/or reassembly) sequence provided for targeting either one component or multiple components.

To determine which components are relevant or critical and for which it can be useful to determine the ease of disassembly and focus on disassembly issues, data is required on which components commonly fail and/or are commonly repaired or which components are commonly upgraded or replaced to bring the product back to its initial performance level. Such data can be found in failure statistics or surveys (IDC, 2016, 2010; SquareTrade, 2009), as well as surveys on consumer expectations on which components need a longer lifetime. Further details are provided in Section 2.1.

6.4. Standardised format for the provision of product information

Ongoing trends on products design should always be taken into account. One of the relevant trends that should be taken into account when sharing product information is the industry 4.0 trend. This trend indicates that an increasing amount of data to optimise different types of processes will be shared as a result of the availability of better IT tools among different actors of the value chain. In line with this, it can be expected that more product data will be shared among, manufacturers, reuse, repair and refurbishing/remanufacturing companies, and all value chain actors in between. For some product brands, valuable information for reuse, repair and refurbishing/remanufacturing is already available and can be used to calculate the ease of disassembly metric. However, currently available product data is not provided in a universal format. Consequently, the required information is not always complete and cannot be easily interpreted or integrated by automated IT tools to, for example, automatically calculate the ease of disassembly for a specific component, or to automatically generate disassembly instructions.

Therefore, future research should focus on the development of a universal format to exchange product information among the different actors of the value chain that could be used for multiple purposes, such as the calculation of the ease of disassembly for specific components for policy compliance, guidelines for disassembly for the purposes of reuse, repair and refurbishing, remanufacturing, etc. For this research, the possibility of extending the oManual (IEEE 1874, 2013) could be investigated. In addition, to avoid the duplication of information and double work for manufactures, future research should investigate how product architecture and, accordingly, disassembly sequences could be recorded in a universal manner. This would facilitate both the automatic calculation of the eDIM metrics for a variety of components and the automatic generation of clearer disassembly instructions for the replacement of multiple components. Finally, as a picture is worth a thousand words', the possibility of complementing product information in a universal format with relevant images should also be investigated.

6.5. Future research

The eDIM method assumes that the operator has access to the right equipment and knows both the sequence to disassemble and the sequence to reassemble a product. These are the best conditions in terms of ease of disassembly. This implies that some decisive elements which, in practice, keep that ideal scenario from happening partially fall outside the scope of the eDIM method, such as availability of instructions, intuitiveness of the disassembly procedure, etc. However, to include these aspects and/or to validate the ease of disassembly and ease of reassembly figures modelled by MOST and included in the eDIM database, in-depth analysis would be required to determine the average disassembly and reassembly efforts under different working conditions for what could be defined as an average connector per connector category included in the eDIM database.

Authors are convinced that the proposed method correctly represents the ease of disassembly and reassembly in average working conditions with perfect product knowledge, as the method is based on the statistically determined average time of basic motions. Accordingly, eDIM makes a good trade-off between the required product information and the accuracy of the ease of disassembly metric, which can be calculated in an unambiguous manner. This links to the general aim of eDIM, which is not to measure the time for disassembly, but to provide a metric that represent a robust and verifiable assessment of the ease of disassembly of products and components.

It should also be considered that, aside from design for disassembly, other product aspects are also highly relevant for reuse, repair and refurbishing/remanufacturing purposes, such as modularity, wear resistance, ability to clean, accessibility or availability of manuals and spare parts. For this reason, future research should investigate how such other product aspects could similarly be assessed in an unambiguous manner. In addition, future research should address whether design innovations could impact the ease of disassembly of the product, and what impact (environmental and economic) the systematic use of design for disassembly solutions could have on the market, for example using the methodology presented in Peeters et al. (2017).

In specific cases, trade-offs might also have to be made by the designer between, for example, the ease of disassembly of a product and other key performance elements (e.g. water and shock resistance). Requirements on ease of disassembly for critical components might be lowered when products are designed with specific durability features, for example higher water and shock resistance (10).

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(10) For example, demonstrated by compliance with international protection marking (IP-code, IEC standard 60529, sometimes interpreted as ingress protection marking) or the equivalent European standard (EN 60529).

7. Conclusions

Strategies to extend product lifetimes (e.g. repair, reuse and product harvesting for component reuse, hardware upgrades, etc.) require facilitated access to product components. Accordingly, ease of disassembly is one of the main factors determining the economic viability of these operations, as confirmed by the visited reuse, repair and refurbishing companies. Nonetheless, as demonstrated by the analysis and interviews performed, the complexity of repair, refurbishing and remanufacturing services of notebook computers has progressively increased over the last decade and this trend will probably continue in the near future due to the increasing complexity of product architecture, and to the use of smaller screws and more adhesives for compact or miniaturised designs. To facilitate repair and reuse operations and to contribute to a more circular economy, the design of new products should also be improved in terms of ease of disassembly and reassembly.

Some policy initiatives to enhance reuse and repair of ICT are currently under discussion in the United States, such as the promotion of design for disassembly and firmware update availability in the framework of the environmental leadership standard on servers (NSF International, 2015), and some law bills currently under discussion in five States (Motherboard, 2015). The objective of these initiatives is to open the market of digital repair to competition, in order to create new jobs and to maintain the economic value of goods in the United States for as long as possible. These initiatives also help to avoid large amounts of electronic waste being generated due to the inability to (affordably) repair broken electronics. Moreover, particularly concerning the United States law bills, the aim is also to protect consumers from the monopolistic practices of digital electronics manufacturers and to make diagnostic and repair information for digital electronic parts and machines available to independent repair providers (New York State Senate, 2017).

However, this analysis also demonstrated the lack of metrics and the absence of harmonised standards to measure and verify product-related reuse, disassembly and recovery efficiency performances. Therefore, the eDIM method was developed in prior research to assess the ease of disassembly of products, by means of a robust and unambiguous calculation process.

To demonstrate the applicability of the eDIM method to small electronic products, the method was further developed and improved in the present study, in order to be applied to the specific case study of notebooks. New types of connections, such as adhesives and cable plugs with a lever, were added to the eDIM database. Furthermore, correction factors for handling small connectors were also included. Optionally, correction factors can also be used when the use of tools with limited availability is needed, or when the origin of every connector must be registered for correct reassembly.

The eDIM method was also further developed to calculate the ease of reassembly metric, so that both complete/partial disassembly and complete/partial reassembly of key components (occurring, for example, during repair and refurbishing/remanufacturing operations) could be assessed.

In the presented study, the eDIM method was applied for assessing both the ease of disassembly and the ease of reassembly of two recent notebooks, using a sequence of complete disassembly and reassembly. In addition, the partial disassembly and reassembly of two main components, the motherboard and the battery, was assessed for the two notebooks.

The presented case studies demonstrated the applicability of the eDIM method to assess the (complete and partial) disassembly and reassembly performance of small electronics, such as notebooks. In addition, it was demonstrated that most information required to calculate the ease of disassembly and ease of reassembly metrics is already available in repair manuals from independent organisations, websites, or in manufacturers’ service manuals.

Applicability

The present study shows that eDIM can be applied in a robust manner to assess the ease of disassembly and reassembly for the purposes of reuse, repair and remanufacturing, for a wide range of product types, and in a verifiable manner. As explained in the presented case studies, the ease of disassembly and reassembly metrics are calculated through eDIM, which is based on MOST values for elementary manual movements. Accordingly, the presented study describes the sequences added to the eDIM database, demonstrates that the database can be expanded with relevant disassembly and reassembly sequences, and proves that these sequences can be converted into eDIM values for any type of manual operation through MOST methodology.

The eDIM method is also applicable to highly complex products, as the number of parts does not affect the practicability of the method. In the case of a complex product, applying eDIM to evaluate the ease of complete disassembly and reassembly only requires the description of disassembly and reassembly sequences, together with a list of connections. While service manuals already list instructions for partial disassembly, in case of specific components, the application of the eDIM method would be more practical if instructions were provided in a more systematic way. For example, disassembly instructions for frequently failing components or components with a high reuse value could already be provided in these manuals.

Calculating the ease of disassembly metric (or the ease of reassembly metric) for a given case study is an activity that requires very little time (11), assuming the disassembly sequence is available and all disassembly operations are listed. Nevertheless, the effort required to apply of eDIM can be further reduced through possible simplifications of the method and of the database. For example, more general connector categories can be defined, and/or specific actions can be removed from the disassembly process, such as identification and/or manipulation. However, it is crucial to calculate the ease of disassembly accurately when eDIM metrics are used to support the design of modular and easy-to-disassemble products. Indeed, eDIM research could play a key role and encourage manufacturers to design products that can be disassembled more quickly. In this regard, we note that the level of detail of eDIM has the advantage of clearly indicating to design teams where there are opportunities to improve product design.

Verifiability

Since the disassembly sequence is a pre-requisite of the method, based on the number of connectors used from a predefined and limited list of options, third-party verifiers (e.g. market surveillance authorities in a policy context) can easily check the correctness of the calculation. Sufficient documentation to support the calculations can be ensured by providing, for example, the exploded diagram of the product with the location of the components and the sequence of operations needed for its disassembly, including for each operation: type of operation; type and number of fastening technique(s) to be unlocked; tool(s) required; warnings (if any) when disassembly operations are affected by the risk of damaging the components; safety requirements and risks (if any) related to the disassembly operations.

A more in-depth verification could imply checking the correctness of the disassembly sequence for the product. In this case, verifiers should check and release the connectors listed in the sequence. Aside from a disassembly toolset, we believe that no dedicated tools are needed to verify whether the main information provided by the manufacturer is correct. The only exception would be the use of adhesives, for which dedicated laboratories might be needed to check the forces needed to release specific adhesive connections. Therefore, we believe that third parties should be capable of performing verifications of eDIM values in a short time and with limited resources in a large majority of cases.

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(11) Compared, for example, to the required time and effort to design, test and further develop electronic products.

Overall, the outcomes of the study show that the eDIM method is characterised in all its parts (especially the database population) by low subjectivity, which allows this approach to be used as a basis for standardised methods. This study can hence contribute as scientific basis for standardisation processes for aspects regarding ease of disassembly, reparability and reusability. The application of the method can also be useful for measures to improve the design of notebook computers.

Annexes

Annex 1. MOST time tables for basic motions

Table 10 — MOST time for general movements (Zandin, 2003)

General move (A B G A B P A)					
Action distance (A)	**Body motion (B)**	**Gain control (G)**	**Placement (P)**	**Index**	**Time [s]**
< = 5 cm			Pick up/Throw away	0	0
Within reach		**Grasp** light objects (simo (12))	**Put**: lay aside/loose fit	1	0.36
1-2 steps	Sit/stand/bend down and stand up 50 %	**Get** light objects non-simo/heavy or bulky/blind or obstructed/disengage/interlocked/collect	**Place:** loose fit blind or obstructed/adjustments/light pressure/double placement	3	1.08
3-4 steps	Bend down and stand up		**Position:** care or precision/heavy pressure/blind or obstructed/intermediate moves	6	2.16
5-7 steps	Sit or stand with adjustments (e.g. move chair or stool into position, sit down comfortably)			10	3.6
8-10 steps	Stand up and bend down/bend down and sit up/climb on or off/through door			16	5.76

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(12) Simo refers to manual actions performed simultaneously by different body members (Zandin, 2003)

Table 11 — MOST time for walking (Zandin, 2003)

Action distance in m (A)	Steps	Index	Time [s]
	3 to 4	6	2.16
	5 to 7	10	3.6
	8 to 10	16	5.76
12		24	8.64
15		32	11.52
20		42	15.12
25		54	19.44
30		67	24.12
38		81	29.16
44		96	34.56
51		113	40.68
59		131	47.16
69		152	54.72
78		173	62.28
88		196	70.56
98		220	79.2
108		245	88.2
120		270	97.2
133		300	108
146		330	118.8

Table 12 — MOST time for fastening or loosening (Zandin, 2003)

Fasten or loosen (F or L)			Index/fastener	Time [s]
Finger action	Spins	Fingers, screwdriver	1	0.36
Wrist action	Turns	Hand, screwdriver, ratchet, T-wrench	3	1.08
	Strokes	Wrench	3	1.08
	Cranks	Wrench, ratchet	3	1.08
	Taps	Hand, hammer	1	0.36
Arm action	Turns	Ratchet	3	1.08
	Turns	T-wrench, two hands	6	2.16
	Strokes	Wrench	3	1.08
	Cranks	Wrench, ratchet	6	2.16
	Strikes	Hammer	3	1.08
Power tool	Screwdriver	Diameter < 6 mm	3	1.08
	Screwdriver	6 mm < diameter < 25 mm	6	2.16

Table 13 — MOST time for cutting, thinking, recording and controlled movements (Zandin, 2003)

Cutting (C)		**Index/fastener**	**Time [s]**
Pliers	Soft 1 hand 1 cut action	3	1.08
Pliers	Medium 1 hand 2 to 3 cut actions	6	2.16
Pliers	Hard 2 hands	10	3.6
Scissors	Per cut	1	0.36
Knife	Per slice	3	1.08
Thinking (T)		**Index/fastener**	**Time [s]**
Inspect	1 point with eyes or fingers	1	0.36
Inspect	3 point with eyes or fingers	3	1.08
Inspect	5 point with eyes or fingers	6	2.16
Inspect	9 point with eyes or fingers	10	3.6
Inspect	14 point with eyes or fingers	16	5.76
Inspect	19 point with eyes or fingers	24	8.64
Inspect	26 point with eyes or fingers	32	11.52
Inspect	34 point with eyes or fingers	42	15.12
Inspect	42 point with eyes or fingers	54	19.44
Read	Text of 3 words	1	0.36
Read	Text of 8 words	3	1.08
Read	Text of 15 words	6	2.16
Read	Text of 24 words	10	3.6
Read	Text of 36 words	24	8.64
Read	Digits or single word	1	0.36
Recording (R)		**Index/fastener**	**Time [s]**
Write	(Check)mark	1	0.36
Write	1 word	6	2.16
Write	2 words	16	5.76
Write	3 words	24	8.64
Controlled movement (M)		**Index/fastener**	**Time [s]**
Push	Button, switch, knob	1	0.36

Annex 2. Time per disassembly or reassembly action

Table 14 — Time per disassembly or reassembly action

Action	MOST sequence	TMU	eDIM value [s/task]
Manipulation by turning product with one hand (product mass < 2 kg — work bench)	|A1B0G1|+|L3|	50	1.8
Manipulation by turning with two hands (2 kg < product mass < 4 kg — work bench)	|A1B0G3|+|L6|	100	3.6
Walking to the other side of the product (operator working kneeling down)	|A6B3A6|	120	4.3
Tool change by fetching and putting back (work bench)	|A1B0G1|+|A1B0P1|	40	1.4
Tool change by standing up and walking to the warehouse (work bench)	|A67B10G1|+|A67B10|+ |A67B10|+|A67B10P1|	3 100	111.6
Positioning of hand or tool relative to connector > 3 mm diameter (work bench)	|A1B0P3A0|	40	1.4
Positioning of hand or tool relative to connector > 3 mm diameter (work bench)	|A1B0P6A0|	70	2.5
Removing separated component (work bench)	|A1B0G1| + |A1B0P1|	40	1.4
Identification — localising connector with visible area < 0.05 mm^2	|T10|	100	3.6
Use of power tool for screw with 3 mm < diameter < 6 mm	|L3|	30	1.1
Use of power tool for screw with 6 mm < diameter < 25 mm	|L6|	60	2.2
Use of finger screwdriver for screw with diameter < 3 mm and < 3 mm thread	5*|L1|	50	1.8
Use of screwdriver for screw with diameter > 3 mm and < 5 mm thread	5*|L3|	150	5.4
Pliers cut with force < 5 N	|C3|	30	1.1
Pliers cut with 5 N < force < 20 N	|C6|	60	2.2
Pliers cut with force > 20 N	|C10|	100	3.6
Finger manipulation with force < 5 N	|L1|	10	0.4
Hand manipulation with 5 N < force < 20 N	|L3|	30	1.1
Two-hand or arm manipulation with force > 20 N	|L6|	60	2.2
Placing released connector within reach (work bench)	|A1B0G1|+|A1B0P1|	40	1.4
Placing released connector within reach and writing three-word annotation (work bench)	|A1B0G1|+|A1B0P1|+|A1B0G1|+|R24|+|A1B0P1|	320	11.5

Action	**MOST sequence**	**TMU**	**eDIM value [s/task]**
Marking cable and cable plug	|A1B0G1|+|R1|+|A1B0P1|	50	1.8
Moving mouse, clicking and reading assembly instructions of 24 words (work bench)	|A1B0G1|+|M1|+|R6|+|A1B0P1|	150	5.4
Reading self-written annotations	|I1|	10	0.4
Preparing and placing new adhesive with high precision (work bench)	|A1B0G3|+|L3|+|A1B0P6|	140	5
Repositioning connector diameter < 3 mm for assembly (work bench)	|A1B0G1|+|A1B0P6|	90	3.2
Repositioning connector diameter > 3 mm for assembly (work bench)	|A1B0G1|+|A1B0P3|	60	2.2
Heating up a surface with nominal length of 5 cm (work bench)	|heat-up time=30 s|	8 333	300

Annex 3. Disassembly guidelines for notebook 1

The guidelines to disassemble notebook 1 are detailed hereinafter. Disassembly guidelines were retrieved on iFixit website (www.ifixit.com).

Step 1 Lower Case

- Removal of the ten screws to disassemble the lower case: two 5-point Pentalobe screws of 8 mm length and <3 mm diameter and eight 5-point Pentalobe screws of 2.5 mm length and <3 mm diameter.
- Removal of the lower case.
- All ten screws are easily identifiable and easy to disassemble. However, to be able to release the 5-point Pentalobe screws a dedicated screwdriver had to be sourced. In addition, the two of the ten screws are longer, which requires some precaution during the re-assembly.

Step 2 Battery (last disassembly step for battery replacement)

- Release of the cable plug of the battery directly without a leaver.
- Removal of the following screws: two 5.2 mm T5 Torx screws, one 6 mm T5 Torx screw and two 2.6 mm T5 Torx screws.
- Removal of the battery.
- The cable plug is not marked, but the cable length is less than 20 mm, so no wrong connection can be made or time is lost to identify the proper position to connect the cable. For the screws it is again important to make an annotation for every screw type to make sure they can be reassembled in the correct position, as they have three different lengths.

Step 3 Right Speaker

- Disconnection of the <3 mm cable plug on the logic board, and use of a spudger to pry the right speaker off the 5 to 10 cm adhesive which was estimated to resist more than 5 N pull-off and shear force and which secures the speaker to the upper case.
- Due to the small size of the cable plug careful and precise handling is required. The adhesive is strong and requires multiple attempts with a spudger to carefully release the speaker and to properly reassemble the speaker the use of a new adhesive would be required.

Step 4 Solid-State Drive

- Removal of the 2.9 mm T5 Torx screw and use of a spudger to help lift the free end of the SSD just enough to grab it with hands.
- Afterward, the SSD can be pulled out of its socket.

Step 5 I/O Board Cable

- Removal of the I/O board cable from its cable plug on the I/O board and removal the I/O board cable up from the soft adhesive securing it to the fan.
- To release the cable plugs either a spudger or hands can be used, as the size of the cable plugs is sufficiently large. The adhesive tape is easy to release, but for proper reassembly a new adhesive should be applied.

Step 6 Fan

- Removal of the following 3 screws securing the fan to the upper case, making the required annotations to record the correct position of every screw: two T5 Torx screws with a length of 5.2 mm and d < 3 mm and one T5 Torx screw with a length of 3.6 mm and d < 3 mm.
- Removal of the cable of the cable socket of < 3mm (without a leaver).
- Whereas it is easy to pull a small cable out of a small connector by hand a spudger or tweezers are required to reassemble the cable.

Step 7 I/O Board

- Disconnection of the I/O board by pulling the power cable away from its socket on the logic board.
- Removal of the microphone ribbon cable straight out of its socket.
- Removal of the camera cable from its socket.
- Opening of the lever with an acting surface smaller than a circle with a diameter of 3 mm of the third cable plug and pulling out the cable.
- Removal of the single T5 Torx screw securing the I/O board to the upper case with a length of 3.6 mm and diameter of < 3 mm.
- Multiple cables are connected to a small component with different sizes, which makes it possible to distinguish which cable has to be connected where, but due to the lack of a clear marking it requires additional time to figure out the correct configuration for reassembly.

Step 8 Left Speaker

- Removal of the left speaker cable out of the cable plug.
- Use of a spudger to pry the left speaker off the 5 to 10 cm length adhesive with a peel-off and shear resistance of > 5 N securing it to the upper case.

Step 9 Microphone

- The disassembly of the microphone cable from the I/O board is already included in disassembly step 7.
- Therefore, the microphone can now directly be pulled away by hand or with the use of a spudger from the side of the upper case and be removed from the upper case.

Step 10 Heat Sink

- Removal of the four T5 Torx screws with a length of 2.5 mm and a diameter < 3 mm securing the heat sink to the logic board. If the heat sink seems to be stuck to the logic board after removing all four screws, a spudger is needed to carefully separate the heat sink from the faces of the CPU and GPU.
- A small amount of heat paste is used to improve the thermal conductivity between the CPU, GPU and the heat sink, which has a small adhesive force which is estimated to be below 5 N and can be easily removed by pulling apart both components. When reassembling the heat sink, it is advised by Ifixit to apply a new layer of thermal paste after removing the remainders of the old thermal paste.

Step 11 Trackpad

- Opening of the leaver of the cable plug (with a spudger) and removal of the trackpad data cable.
- Removal of the six Phillips #00 screws of 1.5 mm length and <3 mm diameter holding the trackpad in place.
- Removal of the trackpad.
- The keyboard ribbon cable completely overlaps the cable plug, which makes it difficult to both identify the cable plug and to access the leaver of the cable plug to release the cable. During the disassembly process of the track path some two hand operations need to be performed. Since these operations can be performed by two hands in parallel no additional time is taken into account to access the cable plug, only the additional time needed to identify it.

Step 12 Logic Board

- Opening of the leaver of the cable plug of the keyboard backlight ribbon cable (with a spudger) and removal of the cable out of its socket.

- Use of a spudger to flip up the leaver of the cable plug to release the trackpad ribbon cable socket and removal of the cable.
- Opening of the black plastic flap stuck to the display data cable lock (with a spudger) to make the lock pop upward and away from the socket.
- Removal of the small rubber gasket from the corner of the upper case near the display data cable.
- Removal of the three T5 Torx screws with a length of 3.6 mm and a diameter <3 mm securing the logic board to the upper case.
- Removal of the logic board assembly out of the upper case.

Step 13 Display

- Peeling off of the six cable loops securing the antenna cables to the upper case.
- Use of a spudger to open up the plastic loops as you de-route the antenna cables through them (for all of the loops).
- Removal of the four T8 Torx screws with a diameter <3 mm securing the two display hinges to the upper case and opening of the display until it is perpendicular to the upper case
- Separation of the screen from the lower case.
- The time required to open the plastic loops is assumed to be include in the peel off time for the plastic loops, as it not considered to be valuable to define an additional connector category for this highly product specific type of connections to retain the cables.

Annex 4. Disassembly guidelines for notebook 2

The guidelines to disassemble notebook 2 are detailed hereinafter. Disassembly guidelines were retrieved on the manufacturer website and on iFixit website (www.ifixit.com).

Step 1 Lower Case

- The system badge is opened using a spudger and subsequently 9 screws are removed. The manufacturer only indicates at the beginning of the manual that the following tools are required: Philips screwdriver, Flat-head screwdriver, Torx #5 (T5) screwdriver, Plastic scribe
- However, no information on which screw type is used for the lower case can be found in the documentation of the manufacturer, whereas this information can be found on the Ifixit website. Since no other dimensions of the screws can be found it is assumed that they are all of the same length and have a diameter of <3mm.

Step 2 Battery

- The battery cable is pulled out from the cable plug on the logic board and the four screws are released. On the Ifixit website it can be found that three Philips screws labeled "M2x2" and one Philips screw labeled "M1.6x4” have to be removed to separate the battery.
- Whereas screws with a different length are used, there is no need for the operator to register which screw should be reassembled at which position as a clear marking is foreseen on the battery for every fastener.

Step 3 Solid State Drive

- The Solid State Drive (SSD) can after removal of a single screw been slide out of its socket.
- Only on the Ifixit website the information that the SSD is retained by a Philips screw could be retrieved.

Step 4 Wireless card

- Based on the information from the manufacturer the wireless card can be released in the same manner as the SSD after removing the wireless-card cables (antennas) from the wireless card.
- Based on the provided images it can be expected that the cable plugs are simple plugs without leavers.
- In the description of the manufacturer it is also described that a label is foreseen which indicates the color of cable that should be connected to every cable plug. Accordingly, no additional marking is required.

Step 5 Speakers

- The speaker cable is disconnected without leaver from the system board and the 4 screws that secure the speakers to the palm-rest assembly can be removed.
- The tapes that secure the speaker cable to the system board can be peeled off.
- No further detail on the type of screw or adhesive could be found. Therefore, 4 of the same Philips screws and a tape with a peel-off force of <5 N are assumed.

Step 6 Heat sink

- The four screws that retain the heat sink are removed.
- The heat sink is pried from the logic board which is attached by thermal paste adhesive.

- The manufacturer’s repair manual states that the original thermal grease can be reused if the original system board and heat sink are reinstalled together. A pull-off force of <5N is assumed as heat paste is commonly characterized by a low adhesive force. The screws are assumed to be all the same and Philips screws.

Step 7 Coin-cell battery

- The coin-cell battery cable is disconnected from the cable plug without leaver from the system board.
- The coin-cell battery is pried from the palm-rest assembly.
- Based on the provided images it can be estimated that the cable plug is <3 mm and has no leaver. Furthermore, the required force to remove the battery is not indicated but assumed to be <5 N pull-off force.

Step 8 Battery-status light cable

- The tape that secures the battery-status light cable to the keyboard-controls board is peeled off.
- The leaver of the cable plug is lifted and the battery-status light cable is disconnected from the keyboard-controls board.

Step 9 Touch pad

- The leaver of the cable plug is lifted and the touch pad cable is disconnected from the system board.
- The touch pad cable is peeled off from the keyboard and palm-rest assembly.
- The four screws that secure the touch pad to the palm-rest assembly are removed.
- The touch pad is lifted from the inner edge and removed from the palm-rest assembly.

Step 10 I/O board cable

- The leaver is lifted from both the cable plugs.
- The I/O board cable is disconnected form the system board and from the I/O board.
- The I/O board cable is peeled off from the keyboard.

Step 11 I/O board

- The two screws that secure the I/O board to the palm-rest assembly are removed.
- The tape that secures the display cable to the I/O board is peeled off.
- The media-card reader cable is disconnected from the I/O board by directly pulling it out of the cable plug.
- The leaver of the cable plug is lifted and the I/O-board cable is disconnected from the I/O board (already included in step 10).
- The I/O board is removed from the palm-rest assembly

Step 12 Keyboard control board (prerequisites: base cover and battery)

- The tape that secures the battery-status light cable to the keyboard-controls board is peeled off.
- The tape that secures the keyboard-controls board to the palm-rest assembly is peeled off.
- The leavers of the cable plugs are lifted and the keyboard-backlight cable, the keyboard cable, the keyboard-controls board cable, and the battery status light cable are disconnected from the keyboard-controls board.
- A spudger is needed to pry up the keyboard-controls board off the palm-rest assembly.

Step 13 Display assembly (prerequisites: base cover, wireless card and battery)

- The single screw that secures the display cable to the I/O board is removed.
- The tape that secure the display cable to the fan and the I/O board is peeled off.
- The media-card reader cable is disconnected from cable plug on the I/O board by simply pulling it out the cable plug.
- The tape from the display-cable bracket is peeled off.
- The two screws that secure the display-cable bracket to the system board are removed.
- The display-cable is lifted and pulled out of the cable plug.
- By opening the palm-rest assembly, the four screws that secure the display hinges to the palm-rest assembly can be removed.
- The palm-rest assembly is removed from the display hinges.

Step 14 System board (prerequisites: base cover, battery, wireless card, solid-state drive and heat sink)

- The tape that secures the antenna cables (already included in step 4) and power-adapter port cable to the system board is peeled off.
- The camera cable, power adapter port cable, and coin-cell battery cable (already included in step 7) are disconnected from the system board.
- The leaver of the cable plug is lifted and the keyboard-controls board cable is disconnected from the system board.
- The tape from the display-cable bracket is peeled off.
- The tapes that secure the speaker cable to the system board are peeled off.
- The fan cable is disconnected from the system board by pulling it out of the cable plug.
- The leavers are lifted and the I/O-board cable and the touch-pad cable are disconnected from the system board (already included in step 11 and 12).
- The screws that secure the display-cable bracket to the system board are removed and the display-cable bracket is released (already included in step13).
- The five screws that secure the system board to the palm-rest assembly are removed.
- The system board is lifted at an angle and removed from under the tabs on the palm-rest assembly.

Step 15 Power-adaptor port (prerequisites base cover, battery, wireless card and system board)

- The single screw that secures the power-adapter port to the palm-rest assembly is removed.
- The cable plug is pulled out (already included in step 14).
- The power-adapter port is removed.

Step 16 Fan (prerequisites: base cover, battery, wireless card and system board)

- The tapes that secure the display cable to the fan are peeled off (already included in step 13).
- The cable from the cable plug on the system board is pulled out (already included in step 14).
- The screw that secures the fan to the palm-rest assembly are removed.

Step 17 Keyboard (prerequisites: base cover, battery, wireless card, speakers, coin-cell battery, heat sink, I/O bard, system board, fan and I/O board cable)

- The leavers of the cable plugs are lifted and the keyboard cable and the keyboard backlight cable is disconnected from the keyboard-controls board.
- The cables are peeled off from the keyboard (already included in step 12).
- The thirty screws that secure the keyboard to the palm-rest assembly are removed.

Step 18 Palm-rest (included in display assembly disassembly)

- The four screws that secure the palm rest to the display hinges are removed.
- The palm rest is removed from the display hinges.

Annex 5. eDIM calculation table for notebook 1 (linked to Table 3)

Component code		Disassembly [s]							Reassembly [s]							**eDIM [s]**
		Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM$_D$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_R$ Reassembly**	
1	Bottom Cover	1.4	0.0	0.0	20.2	25.9	1.4	**48.9**	0.0	0.0	0.0	20.2	40.3	1.4	**61.9**	**110.8**
	Bottom Cover	0.0	0.0	0.0	5.0	6.5	0.0	**11.5**	1.4	0.0	0.0	5.0	10.1	0.0	**16.6**	**28.1**
2	Battery	0.0	0.0	0.0	1.4	0.4	1.4	**3.2**	0.0	0.0	0.0	1.4	1.1	1.4	**3.9**	**7.1**
3	Battery	1.4	0.0	0.0	5.0	6.5	0.0	**13.0**	0.0	0.0	0.0	5.0	10.1	0.0	**15.1**	**28.1**
	Battery	0.0	0.0	0.0	2.5	3.2	0.0	**5.8**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**13.3**
	Battery	0.0	0.0	0.0	5.0	6.5	0.0	**11.5**	1.4	0.0	0.0	5.0	10.1	0.0	**16.6**	**28.1**
	Battery	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	**3.6**
4	Right speaker	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	**8.6**
	Right speaker	1.4	0.0	0.0	5.0	4.3	0.0	**10.8**	1.4	0.0	0.0	5.0	10.1	0.0	**16.6**	**27.4**
5	Solid State Drive	1.4	0.0	0.0	2.5	3.2	1.4	**8.6**	1.4	0.0	0.0	2.5	5.0	1.4	**10.4**	**19.0**
	Solid State Drive	1.4	0.0	0.0	1.4	0.4	0.0	**3.2**	1.4	0.0	0.0	1.4	0.4	0.0	**3.2**	**6.5**
6	I/O board cable	0.0	0.0	0.0	1.4	0.4	1.4	**3.2**	0.0	0.0	0.0	1.4	1.1	1.4	**3.9**	**7.1**
	I/O board cable	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
	I/O board cable	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	1.1	0.0	**2.5**	**4.3**
7	Fan	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	**8.6**
	Fan	1.4	0.0	0.0	5.0	6.5	0.0	**13.0**	0.0	0.0	0.0	5.0	10.1	0.0	**15.1**	**28.1**
	Fan	0.0	0.0	0.0	2.5	3.2	0.0	**5.8**	1.4	0.0	0.0	2.5	5.0	0.0	**9.0**	**14.8**
8	I/O board	0.0	0.0	0.0	1.4	0.4	1.4	**3.2**	0.0	0.0	0.0	1.4	1.1	1.4	**3.9**	**7.1**
	I/O board	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**5.8**

Component code		Disassembly [s]							Reassembly [s]							eDIM [s]
		Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM$_D$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_R$ Reassembly**	
	I/O board	1.4	0.0	0.0	2.5	0.7	0.0	**4.7**	1.4	0.0	0.0	2.5	0.4	0.0	**4.3**	**9.0**
	I/O board	1.4	0.0	0.0	2.5	3.2	0.0	**7.2**	1.4	0.0	0.0	2.5	5.0	0.0	**9.0**	**16.2**
9	Left speaker	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	**8.6**
	Left speaker	1.4	0.0	0.0	5.0	4.3	0.0	**10.8**	1.4	0.0	0.0	5.0	10.1	0.0	**16.6**	**27.4**
10	Microphone	0.0	0.0	0.0	1.4	0.4	1.4	**3.2**	0.0	0.0	0.0	1.4	0.4	1.4	**3.2**	**6.4**
11	Heat sink	1.4	0.0	0.0	10.1	13.0	1.4	**25.9**	1.4	0.0	0.0	10.1	20.2	1.4	**33.1**	**59.0**
	Heat sink	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
12	Trackpad	1.4	0.0	0.0	2.5	0.7	1.4	**6.1**	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	**10.4**
	Trackpad	0.0	3.6	0.0	2.5	0.7	0.0	**6.8**	1.4	3.6	0.0	2.5	0.4	0.0	**7.9**	**14.8**
	Trackpad	1.4	0.0	1.8	15.1	19.4	0.0	**37.8**	1.4	0.0	1.8	15.1	30.2	0.0	**48.6**	**86.4**
13	Logic board	1.4	0.0	0.0	2.5	0.7	1.4	**6.1**	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	**10.4**
	Logic board	0.0	0.0	0.0	2.5	0.7	0.0	**3.2**	1.4	0.0	0.0	2.5	0.4	0.0	**4.3**	**7.6**
	Logic board	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	**3.6**
	Logic board	0.0	0.0	0.0	5.0	0.7	0.0	**5.8**	0.0	0.0	0.0	5.0	0.7	0.0	**5.8**	**11.5**
	Logic board	1.4	0.0	0.0	7.6	9.7	0.0	**18.7**	1.4	0.0	0.0	7.6	15.1	0.0	**24.1**	**42.8**
14	Display	0.0	0.0	0.0	15.1	2.2	1.4	**18.7**	0.0	0.0	0.0	15.1	30.2	1.4	**46.8**	**65.4**
	Display	1.4	0.0	1.8	10.1	13.0	0.0	**26.3**	1.4	0.0	1.8	10.1	20.2	0.0	**33.5**	**59.8**
	Total (s)	**22**	**4**	**4**	**163**	**140**	**18**	**350**	**22**	**4**	**4**	**163**	**257**	**18**	**466**	**816**

Annex 6. eDIM calculation table for notebook 2 (linked to Table 4)

Component code		Disassembly [s]							Reassembly [s]							**eDIM [s]**
		Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM$_D$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_R$ Reassembly**	
1	Lower case	1.4	0.0	0.0	1.4	0.4	1.4	**4.6**	1.4	0.0	0.0	1.4	0.4	1.4	**4.6**	**9.3**
	Lower case	1.4	0.0	0.0	22.7	29.2	0.0	**53.3**	1.4	0.0	0.0	22.7	45.4	0.0	**69.5**	**122.8**
	Lower case	1.4	0.0	0.0	1.4	0.4	0.0	**3.2**	1.4	0.0	0.0	1.4	0.4	0.0	**3.2**	**6.5**
2	Battery	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	**8.6**
	Battery	1.4	0.0	0.0	7.6	9.7	0.0	**18.7**	0.0	0.0	0.0	7.6	15.1	0.0	**22.7**	**41.4**
	Battery	0.0	0.0	0.0	2.5	3.2	0.0	**5.8**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**13.3**
3	Solid State Drive	0.0	0.0	0.0	2.5	3.2	1.4	**7.2**	1.4	0.0	0.0	2.5	5.0	1.4	**10.4**	**17.6**
	Solid State Drive	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	**3.6**
4	Wireless card	0.0	0.0	0.0	5.0	0.7	1.4	**7.2**	0.0	0.0	0.0	5.0	0.7	1.4	**7.2**	**14.3**
	Wireless card	1.4	0.0	0.0	2.5	3.2	0.0	**7.2**	1.4	0.0	0.0	2.5	5.0	0.0	**9.0**	**16.2**
	Wireless card	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	**3.6**
5	Speakers	0.0	0.0	0.0	2.9	0.7	1.4	**5.0**	0.0	0.0	0.0	2.9	2.2	1.4	**6.4**	**11.4**
	Speakers	1.4	0.0	0.0	10.1	13.0	0.0	**24.5**	1.4	0.0	0.0	10.1	20.2	0.0	**31.7**	**56.2**
	Speakers	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
6	Heat sink	1.4	0.0	0.0	10.1	13.0	1.4	**25.9**	1.4	0.0	0.0	10.1	20.2	1.4	**33.1**	**59.0**
	Heat sink	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
7	Coin-cell battery	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	**8.6**
	Coin-cell battery	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**

Component code		Disassembly [s]							Reassembly [s]							**eDIM [s]**
		Tool change	Identification	Manipulation	Positioning	Disconnection	Removal	**eDIM$_D$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_R$ Reassembly**	
8	Battery-status light cable	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	0.0	0.0	0.0	2.5	5.0	1.4	**9.0**	**13.2**
	Battery-status light cable	1.4	0.0	0.0	2.5	0.7	0.0	**4.7**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**7.6**
9	Touch pad	0.0	0.0	0.0	2.5	0.7	1.4	**4.6**	1.4	0.0	0.0	2.5	0.4	1.4	**5.7**	**10.4**
	Touch pad	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
	Touch pad	1.4	0.0	0.0	10.1	13.0	0.0	**24.5**	1.4	0.0	0.0	10.1	20.2	0.0	**31.7**	**56.2**
	Touch pad	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	**3.6**
10	I/O-board cable	1.4	0.0	0.0	5.0	1.4	1.4	**9.3**	1.4	0.0	0.0	5.0	0.7	1.4	**8.6**	**17.9**
	I/O-board cable	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
11	I/O board	1.4	0.0	0.0	5.0	6.5	1.4	**14.4**	1.4	0.0	0.0	5.0	10.1	1.4	**18.0**	**32.3**
	I/O board	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
	I/O board	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**5.8**
	I/O board	1.4	0.0	0.0	2.5	0.7	0.0	**4.7**	1.4	0.0	0.0	2.5	0.4	0.0	**4.3**	**9.0**
12	Keyboard control board	0.0	0.0	0.0	2.5	0.4	1.4	**4.3**	0.0	0.0	0.0	2.5	5.0	1.4	**9.0**	**13.2**
	Keyboard control board	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
	Keyboard control board	1.4	0.0	0.0	2.5	0.7	0.0	**4.7**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**7.6**
	Keyboard control board	0.0	0.0	0.0	2.5	0.7	0.0	**3.2**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**6.1**
	Keyboard control board	0.0	0.0	0.0	2.5	0.7	0.0	**3.2**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**6.1**
	Keyboard control board	0.0	0.0	0.0	2.5	0.7	0.0	**3.2**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**6.1**
	Keyboard control board	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	1.4	0.0	0.0	1.4	0.4	0.0	**3.2**	**5.0**

Component code		**Disassembly [s]**							**Reassembly [s]**							**eDIM [s]**
		Tool change	Identification	Manipulation	Positioning	Disconection	Removal	**eDIM$_D$ Disassembly**	Tool change	Identification	Manipulation	Positioning	Fastening	Addition	**eDIM$_R$ Reassembly**	
13	Display assembly	1.4	0.0	0.0	2.5	3.2	1.4	**8.6**	1.4	0.0	0.0	2.5	5.0	1.4	**10.4**	**19.0**
	Display assembly	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
	Display assembly	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**5.8**
	Display assembly	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	5.0	0.0	**7.6**	**10.4**
	Display assembly	1.4	0.0	0.0	2.5	3.2	0.0	**7.2**	1.4	0.0	0.0	2.5	5.0	0.0	**9.0**	**16.2**
	Display assembly	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	1.1	0.0	**2.5**	**4.3**
	Display assembly	1.4	0.0	1.8	10.1	13.0	0.0	**26.3**	1.4	0.0	1.8	10.1	20.2	0.0	**33.5**	**59.8**
	Display assembly	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	**3.6**
14	System board	0.0	0.0	0.0	5.0	0.7	1.4	**7.2**	0.0	0.0	0.0	5.0	10.1	1.4	**16.5**	**23.7**
	System board	0.0	0.0	0.0	5.0	0.7	0.0	**5.8**	0.0	0.0	0.0	5.0	0.7	0.0	**5.8**	**11.5**
	System board	1.4	0.0	0.0	2.5	0.7	0.0	**4.7**	1.4	0.0	0.0	2.5	0.4	0.0	**4.3**	**9.0**
	System board	0.0	0.0	0.0	5.0	0.7	0.0	**5.8**	0.0	0.0	0.0	5.0	10.1	0.0	**15.1**	**20.9**
	System board	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	0.0	0.0	0.0	2.5	0.4	0.0	**2.9**	**5.8**
	System board	1.4	0.0	0.0	12.6	16.2	0.0	**30.2**	1.4	0.0	0.0	12.6	25.2	0.0	**39.2**	**69.5**
	System board	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	0.0	0.0	0.0	1.4	0.4	0.0	**1.8**	**3.6**
15	Power-adaptor port	1.4	0.0	0.0	2.5	3.2	1.4	**8.6**	0.0	0.0	0.0	2.5	5.0	1.4	**9.0**	**17.6**
16	Fan	0.0	0.0	0.0	2.5	3.2	1.4	**7.2**	0.0	0.0	0.0	2.5	5.0	1.4	**9.0**	**16.1**
17	keyboard	0.0	0.0	0.0	75.6	97.2	1.4	**174.2**	1.4	0.0	0.0	75.6	151.2	1.4	**229.6**	**403.8**
	Total(s)	**27**	**0**	**2**	**283**	**253**	**24**	**589**	**27**	**0**	**2**	**283**	**451**	**24**	**787**	**1376**

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